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CONTENTS

	Page
Proceedings of the Twenty-sixth Annual Meeting of the Geological Society of America, held at Princeton, New Jersey, December 30 and 31, 1913, and January 1, 1914; EDMUND OTIS HOVEY, <i>Secretary</i>	1
Session of Tuesday, December 30.....	4
Election of Auditing Committee.....	5
Election of officers.....	5
Election of Fellows.....	6
Memorial of William M. Fontaine; by T. L. WATSON.....	6
Memorial of Thomas Moore Jackson; by I. C. WHITE.....	13
Events leading up to the organization of the Geological Society of America; by J. J. STEVENSON.....	15
Review of the early history of the Society; by HERMAN L. FAIRCHILD.....	17
History of the Bulletin; by J. STANLEY-BROWN.....	24
Review of the formation of geological societies in the United States; by N. H. WINCHELL.....	27
Titles and abstracts of papers presented in general session and discussions thereon.....	30
Mechanics of formation of arcuate mountains [abstract]; by W. H. HOBBS.....	30
Early Tertiary glaciation in the San Juan region of Colorado [abstract and discussion]; by WALLACE WALTER ATWOOD.....	31
Origin of pillow lavas [abstract and discussion]; by J. VOLNEY LEWIS.....	32
Titles and abstracts of papers presented before the First Section and discussions thereon.....	33
Earthquake sea waves [abstract and discussion]; by HARRY FIELDING REID.....	33
Recent earthquakes in Panama and their causes; by DONALD F. MACDONALD.....	34
Criticism of the Hayfordian conception of isostasy regarded from the standpoint of geology [abstract]; by W. H. HOBBS.....	34
Earth-movements in the Minnesota portion of the Lake Agassiz basin during and since the lake occupancy [abstract and discussion]; by FRANK LEVERETT.....	34
Time measures in the Niagara Gorge and their application to Great Lake history [abstract and discussion]; by FRANK B. TAYLOR.....	35
Illustration of intraformational corrugation [abstract and discussion]; by JOHN M. CLARKE.....	37
Illustrations of the recent exposure of the Saratoga Springs [abstract]; by JOHN M. CLARKE.....	38
An alternative explanation of the origin of the Saratoga mineral waters [abstract and discussion]; by R. RUEDEMANN.....	38
Titles and abstracts of papers presented before the Second Section and discussions thereon.....	39

	Page
Characteristics of a corrosion conglomerate [abstract]; by F. W. SARDESON	39
A pre-Cambrian unconformity in Vermont [abstract]; by ARTHUR KEITH	39
Reconnaissance of the Algonkian rocks of southeast Newfoundland [abstract]; by ARTHUR BUDDINGTON.....	40
Sections illustrating the lower part of the Silurian system of southwestern Ontario [abstract]; by MERTON Y. WILLIAMS....	40
Evidence of climatic oscillations in the Permo-Carboniferous beds of Texas [abstract]; by E. C. CASE.....	41
Geologic history of the Florida coral-reef tract and comparisons with other coral-reef areas [abstract]; by THOMAS WAYLAND VAUGHAN	41
Titles and abstracts of papers presented before the Third Section and discussions thereon.....	43
Graphic method of representing the chemical relations of a petrographic province [abstract and discussion]; by FRANK D. ADAMS	43
Effusive and intrusive in the quantitative classification [abstract]; by ALFRED C. LANE.....	43
Change in the crystallographical and optical properties of quartz with rise in temperature [abstract and discussion]; by FRED E. WRIGHT	44
Mode of formation of certain gneisses in the highlands of New Jersey [abstract and discussion]; by C. N. FENNER.....	44
Magmatic differentiation and assimilation in the Adirondack region [abstract and discussion]; by WILLIAM J. MILLER.....	45
New point in the geology of the Adirondacks [abstract and discussion]; by J. F. KEMP.....	47
Minerals from the ore deposits at Park City, Utah [abstract and discussion]; by FRANK R. VAN HORN.....	47
Deepest boring in West Virginia [abstract]; by I. C. WHITE.....	48
Presidential address: Pioneers in Gulf Coastal Plain geology; by E. A. SMITH.....	48
Session of Wednesday, December 31.....	48
Report of Committee on Photographs.....	48
Report of Committee on Geological Nomenclature.....	49
Report of Auditing Committee.....	49
Amendment to the By-Laws.....	49
Bibliography of formation names.....	50
Report of the Council.....	51
Secretary's report.....	51
Treasurer's report.....	53
Editor's report.....	56
Title and abstracts of papers presented in general session and discussions thereon.....	58
Improvements in methods of investigating highly carbonized materials and their bearing on the mode of deposition of coal [abstract]; by EDWARD CHARLES JEFFREY.....	58

CONTENTS

v

Page

Origin of oolites and the oolitic texture in rocks [abstract and discussion]; by THOMAS CLACHAR BROWN.....	58
Precise leveling and the problem of coastal subsidence [abstract and discussion]; by DOUGLAS W. JOHNSON.....	59
Some historical evidence of coastal subsidence in New England [abstract and discussion]; by CHARLES A. DAVIS.....	61
Pleistocene marine submergence of the Connecticut and Hudson valleys [abstract and discussion]; by HERMAN L. FAIRCHILD..	63
Titles and abstracts of papers presented before the First Section and discussion thereon.....	65
Cause of the postglacial deformation of the Ontario region [abstract and discussion]; by J. W. SPENCER.....	65
Origin of dolomite [abstract]; by FRANCIS M. VAN TUYL.....	66
Flattening of limestone gravel boulders by solution; by JOHAN AUGUST UDDEN.....	66
High-level loop channel [abstract]; by T. C. HOPKINS.....	68
Divergent ice-flow on the plateau northeast of the Catskill Mountains as revealed by ice-molded topography; by JOHN L. RICH.	68
Length and character of the earliest interglacial beds [abstract]; by A. P. COLEMAN.....	71
Age of the glacial deposits in the Don Valley, Toronto, Ontario [abstract]; by G. FREDERICK WRIGHT.....	71
Titles and abstracts of papers presented before the Third Section and discussions thereon.....	73
Manganese deposits of Conception and Trinity bays, Newfoundland [abstract]; by NELSON C. DALE.....	73
Geology of the Wabana iron ore of Newfoundland [abstract]; by ALBERT O. HAYES.....	74
Geology of the Cumberland-Diamond Hill district, Massachusetts-Rhode Island [abstract]; by CHARLES H. WARREN and SIDNEY POWERS	75
Sedimentary character of garnetiferous hornblende schist, Hanover, New Hampshire [abstract]; by JOHN WESLEY MERRITT..	75
Oolites of the Chimneyhill formation, Oklahoma [abstract and discussion]; by CHESTER A. REEDS.....	75
Temiskamite, a new nickel arsenide from Ontario [abstract]; by T. L. WALKER.....	76
Oolitic and pisolitic barite from the Saratoga oil field, Texas; by E. S. MOORE.....	77
Annual dinner.....	80
Session of Thursday, January 1.....	80
Some observations of the Volcano Kilauea in action [abstract]; by ARTHUR L. DAY.....	80
Titles and abstracts of papers presented in general session and discussions thereon.....	81
Stratigraphy of Red Beds of New Mexico [abstract and discussion]; by N. H. DARTON.....	81
Solar hypothesis of climatic changes [abstract]; by ELLSWORTH HUNTINGTON	82

	Page
Vote of thanks.....	83
Titles and abstracts of papers presented before the First Section and discussions thereon.....	84
Occurrence of glacial drift on the Magdalen Islands [abstract]; by J. W. GOLDTHWAIT.....	84
Evidence of a glacial ice-dam in the Allegheny River between Warren, Pennsylvania, and Tionesta, Pennsylvania [abstract]; by G. FREDERICK WRIGHT.....	84
Preglacial Miami and Kentucky rivers [abstract and discussion]; by N. M. FENNEMAN.....	85
Delaware terraces [abstract]; by N. H. WINCHELL.....	86
Sublacustrine glacial erosion in Montana [abstract]; by WILLIAM M. DAVIS.....	86
Glacial Lake Missoula [abstract]; by R. W. STONE.....	87
Physiographic relations of serpentine, with special reference to the serpentine stock of Staten Island, New York [abstract and discussion]; by WILLIAM OTIS CROSBY.....	87
Erosive potential of desert waters [abstract]; by CHARLES R. KEYES.....	88
Submarine topography in Glacier Bay, Alaska [abstract]; by LAWRENCE MARTIN.....	88
Buried gorge of the Hudson River and geologic relations of Hudson syphon of the Catskill Aqueduct [abstract]; by W. O. CROSBY.....	89
Abstract of papers presented before the Third Section and discussion thereon.....	90
Composition of bornite and its relation to other sulfominerals [abstract and discussion]; by EDWARD H. KRAUS.....	90
Genesis of glauconite [abstract]; by CHASE PALMER.....	91
Crystallization of certain pyroxene-bearing artificial melts [abstract]; by N. L. BOWEN.....	91
Physical-chemical system, lime-alumina-silica and its geological significance [abstract]; by FRED E. WRIGHT and G. A. RANKIN.....	92
Constitution and By-Laws.....	93
References to adoption and changes.....	93
Constitution.....	93
By-Laws.....	97
Publication rules of the Geological Society of America.....	101
Register of the Princeton Meeting, 1913.....	105
Officers, Correspondents, and Fellows of the Geological Society of America.....	107
Proceedings of the Fourteenth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, April 11 and 12, 1913; GEORGE D. LOUDERBACK, <i>Secretary</i>	119
Session of Friday, April 11.....	120
Some graphic methods for the solution of geologic problems; by W. S. TANGIER SMITH.....	120
Polarized skylight and the petrographic microscope; by W. S. Tangier Smith.....	120

	Page
Apparent limits of former glaciation in the northern coast ranges of California [abstract]; by R. S. HOLWAY.....	120
Variations in rainfall in California [abstract]; by WILLIAM G. REED	121
Coal-bearing Eocene of western Washington. I. Pierce County [abstract]; by WILLIAM F. JONES.....	121
Nature of the later deformations in certain ranges of the Great Basin; by CHARLES L. BAKER.....	122
Annual dinner.....	123
Geology of the southern end of the San Joaquin Valley [abstract]; by G. C. GESTER.....	123
Session of Saturday, April 12, 1913.....	123
Physiographic features of the Haywards Rift [abstract]; by DAVID M. DURST.....	123
Climatic provinces of the United States west of the Rockies [abstract]; by WILLIAM G. REED.....	124
Occurrence of free gold in granodiorite of Siskiyou County, California [abstract]; by A. F. ROGERS and E. S. BOUNDEY.....	124
Nomenclature of minerals [abstract]; by A. F. ROGERS.....	124
Some contact metamorphic minerals in crystalline limestone at Crestmore, near Riverside, California [abstract]; by ARTHUR S. EAKLE	125
Election of officers.....	125
Resistant surfaces developed by erosion and deposition in the arid and semi-arid regions of Arizona; by C. F. TOLMAN, JR.....	125
Occurrence of stibnite and metastibnite at Steamboat Springs, Nevada [abstract]; by J. C. JONES.....	126
Devonian of the Upper Connecticut Valley; by C. H. HITCHCOCK..	126
Register of the Berkeley meeting.....	126
Proceedings of the Fifth Annual Meeting of the Paleontological Society, held at Princeton, New Jersey, December 31, 1913, and January 1, 1914;	
R. S. BASSLER, <i>Secretary</i>	127
Session of Wednesday, December 31.....	129
Presidential address: Cambrian of western North America; by C. D. WALCOTT.....	130
Symposium on "The Close of the Cretaceous and Opening of Eocene Time in North America".....	130
Session of Thursday, January 1.....	130
Completion of symposium.....	130
Report of the Council.....	130
Secretary's report.....	131
Treasurer's report.....	132
Appointment of Auditing Committee.....	133
Election of officers and members.....	133
New business and announcements.....	134
Section of Invertebrate, Paleobotanic, and General Paleontology.	135
Use of crinoid arms in studies of phylogeny [abstract]; by ELVIRA WOOD.....	135
Western extension of some Paleozoic faunas in southeastern Missouri [abstract]; by STUART WELLER and M. G. MEHL..	135

	Page
Mounting of rock and fossil specimens with sulphur [abstract]; by CHESTER A. REEDS.....	136
Restoration of Paleozoic Cephalopods; by RUDOLPH RUEDEMANN	136
Some new paleogeographic maps of North America [abstract]; by A. W. GRABAU.....	136
Devonian black shale of Michigan, Ohio, Canada, and western New York interpreted as a Paleozoic delta deposit; by A. W. GRABAU.....	137
Lower Paleozoic section of the Alaska-Yukon boundary [abstract]; by L. D. BURLING.....	137
Cambrian brachiopoda, a study of their inclosing sediments [abstract]; by L. D. BURLING.....	137
Calcareous algae from the Silurian; by FRITZ BERCKHEIMER..	137
Cambrian and Ordovician faunas of southeastern Newfoundland [abstract]; by GILBERT VAN INGEN.....	138
"Laramie" ? Puerco, and Torrejon in the San Juan Basin, New Mexico [abstract]; by WILLIAM J. SINCLAIR.....	138
Phylogenetic development of the hexactinellid dictyosponges, as indicated by the ontogeny of an Upper Devonian species; by JOHN M. CLARKE.....	138
Minutes of the sectional meeting of Vertebrate Paleontology....	139
Final results in the phylogeny of the Titanotheres; by H. F. OSBORN	139
Restoration of some Pyrotherium mammals; by FREDERIC B. LOOMIS	139
Analysis of the Pyrotherium fauna; by FREDERIC B. LOOMIS..	140
New methods in restoring Eotitanops and Brontotherium; by H. F. OSBORN.....	140
Structure and affinities of the Multituberculata; by ROBERT BROOM	140
Note on the American Triassic genus <i>Placerias</i> Lucas; by ROBERT BROOM.....	141
Skeleton of <i>Notharctus</i> , an Eocene Lemuroid; by W. K. GREGORY	141
Phyletic relationships of the Lemuroidea; by W. K. GREGORY.	141
Restoration of the world series of elephants and mastodons; by H. F. OSBORN.....	142
Fauna of the Cumberland Pleistocene cave deposit; by J. W. GIDLEY	142
Rectigradations and alloimetrans in relation to the conception of the "Mutations" of Waagen; by H. F. OSBORN.....	142
Miocene dolphin from California; by RICHARD S. LULL.....	142
New accessions to the exhibition series at Yale Museum; by RICHARD S. LULL.....	143
New mastodon find in Connecticut; by RICHARD S. LULL....	143
Notes on <i>Camarosaurus</i> Cope; by CHARLES C. MOOK.....	143
Relations of the American Pelycosaurs to the South African dinocephalians; by ROBERT BROOM.....	143

	Page
Results of recent work at Rancho la Brea; by JOHN C. MERRIAM	143
Systematic position of the Mylodont sloths from Rancho la Brea; by CHESTER STOCK.....	143
Geology of the Uinta formation; by EARL DOUGLASS.....	144
New Titanotheres from the Uinta formation of Utah; by O. A. PETERSON	144
Report of progress in the revision of the Lower Eocene faunas; by W. D. MATTHEW.....	144
Group of twenty-six associated skeletons of Leptomeryx from the White River Oligocene; by E. S. RIGGS.....	145
Register of the Princeton meeting, 1913.....	145
Officers, correspondents, and members of the Paleontological Society	146
Minutes of the Fourth Annual Meeting of the Pacific Coast Section of the Paleontological Society; by E. DICKERSON, <i>Secretary</i>	150
Fauna of the <i>Scutella breweriana</i> zone of the Upper Monterey series [abstract]; by B. L. CLARK.....	151
Fauna of Lower Fernando series [abstract]; by WALTER A. ENGLISH	151
Some West Coast Mactridæ [abstract]; by EARLE PACKARD..	151
Observations on the use of the percentage method in determining the age of Tertiary formations in California; by B. MARTIN.....	152
Geological relations between the Cretaceous and Tertiary of southern California [abstract]; by CLARENCE A. WARING..	152
Echinoderms of the San Pablo [abstract]; by W. S. W. KEW..	152
Fauna of the San Pablo series [abstract]; by B. L. CLARK..	152
Terrestrial Oligocene of the Basin region and its relation to the marine Oligocene of the Pacific Coast province; by JOHN C. MERRIAM.....	153
Faunal relations of the San Lorenzo Oligocene to the Eocene in California [abstract]; by ROY E. DICKERSON.....	153
Vaqueros of the Santa Monica Mountains of southern California [abstract]; by HAROLD HANNIBAL.....	153
Lower Miocene of Washington [abstract]; by CHARLES E. WEAVER	153
Fauna of the Oligocene (?) of Oregon [abstract]; by F. M. ANDERSON	154
Faunal zones of the Martinez Eocene of California [abstract]; by ROY E. DICKERSON.....	154
Comparison of the oysters of the lower and upper horizons of the Miocene of the Muir syncline [abstract]; by WILLIAM V. CRUESS.....	154
Antelopes in the fauna of Rancho la Brea [abstract]; by ASA C. CHANDLER.....	155
Vertebrate fauna of the Triassic limestones at Cow Creek, Shasta County, California [abstract]; by H. C. BRYANT...	155

	Page
Some physical features of Hawver Cave; by J. C. HAWVER..	155
Hawver Cave: Its Pleistocene fauna [abstract]; by CHESTER STOCK	155
Mammalian fauna of the Pleistocene beds at Manix in the Mohave Desert region [abstract]; by JOHN P. BUWALDA..	156
Occurrence of mammalian remains at Rancho la Brea [abstract]; by R. C. STRONER.....	156
Correlation of the Tertiary formations of the Pacific Coast and Basin regions of western United States; by J. C. MERRIAM	156
Vertebrate fauna of the Orindan and Siestan formations [abstract]; by J. C. MERRIAM.....	156
Pioneers in Gulf Coastal Plain geology: Presidential address by E. A. SMITH	157
Geological section along the Yukon-Alaska boundary line between Yukon and Porcupine rivers; by D. D. CAIRNES.....	179
Age of the Don River glacial deposits, Toronto, Ontario; by G. F. WRIGHT	205
Evidence of a glacial dam in the Allegheny River between Warren, Pennsylvania, and Tionesta; by G. F. WRIGHT.....	215
Pleistocene marine submergence of the Connecticut and Hudson valleys; by H. L. FAIRCHILD.....	219
Magmatic differentiation and assimilation in the Adirondack region; by W. J. MILLER	243
Medina and cataract formations of the Siluric of New York and Ontario; by C. SCHUCHERT.....	277
Close of the Cretaceous and opening of Eocene time in North America; by H. F. OSBORN.....	321
Cretaceous-Tertiary boundary in the Rocky Mountain region; by F. H. KNOWLTON	325
Boundary between Cretaceous and Tertiary in North America as indicated by stratigraphy and invertebrate faunas; by T. W. STANTON.....	341
Cretaceous Eocene correlation in New Mexico, Wyoming, Montana, Alberta; by B. BROWN.....	355
Evidence of the Paleocene vertebrate fauna on the Cretaceous-Tertiary problem; by W. D. MATTHEW.....	381
Recent results in the phylogeny of the Titanotheres; by H. F. OSBORN....	403
New methods of restoring Eotitanops and Brontotherium; by H. S. OSBORN	406
Restoration of the world series of elephants and mastodons; by H. F. OSBORN	407
Rectigradations and allometrons in relation to the conceptions of the "Mutations of Waagen," of species, genera, and phyla; by H. F. OSBORN.	411
Geology of the Uinta formation; by EARL DOUGLASS.....	417
Cambrian and related Ordovician brachiopoda—a study of their inclosing sediments; by L. D. BURLING.....	421
Geology of the Diamond Hill-Cumberland district in Rhode Island-Massachusetts; by C. H. WARREN and SIDNEY POWERS.....	435
The solar hypothesis of climatic changes; by E. HUNTINGTON.....	477

	Page
Origin of pillow lavas; by J. V. LEWIS.....	591
Mechanical composition of clastic sediments; by J. A. UDDEN.....	655
Origin of oolites and the oolitic texture in rocks; by T. C. BROWN.....	745
Index to volume 25.....	781

ILLUSTRATIONS

PLATES

Plate		Page
1—	WATSON: Portrait of W. M. Fontaine.....	6
“ 2—	WHITE: Portrait of T. M. Jackson.....	13
“ 3—	UDDEN: Limestone boulders.....	67
“ 4—	CAIRNES: Tindir sections in vicinity of Porcupine River.....	188
“ 5	“ Cambrian and pre-Cambrian (?) beds, Yukon-Alaska boundary line.....	190
“ 6	“ Mountain groups composed almost entirely of Paleozoic limestones and dolomites.....	193
“ 7	“ Typical exposures of Mesozoic beds, British Columbia.....	201
“ 8	“ Mesozoic beds, Kandik River.....	202
“ 9—	WRIGHT: Glacial topography, Glade Run Terrace, Pennsylvania.....	215
“ 10—	FAIRCHILD: Approximate marine plane in the Connecticut Valley.....	220
“ 11	“ Pleistocene marine submergence of the Connecticut and Hudson-Champlain valleys.....	234
“ 12—	SARDESON: Flat sharp-edged pebbles from the Galena formation.....	265
“ 13—	SCHUCHERT: Contacts between Siluric and Ordovician (Cincinnati) systems.....	286
“ 14	“ Contacts of the Cataract in Ontario, Canada.....	287
“ 15—	LEWIS: Pillow basalt.....	654
“ 16	“ Pillow basalt.....	654
“ 17	“ Pillow basalt and glaciated surface of Ely greenstone.....	654
“ 18	“ Pillow lava and “ellipsoidal structure in intrusive basalt”.....	654
“ 19	“ Pillow surfaces of ellipsoidal greenstone and cross-section of radial jointing of pillow lava.....	654
“ 20	“ Pillow lava and pillow diabase.....	654
“ 21	“ Pillow lava features.....	654
“ 22	“ Pillow lava at Kilauea, Hawaii.....	654
“ 23	“ Pillow lava.....	654
“ 24	“ Boulder of pillow basalt.....	654
“ 25	“ Spheroidal weathering of basalt.....	654
“ 26—	BROWN: Micro-sections of oolitic structures.....	778
“ 27	“ Micro-sections of oolitic structures.....	779
“ 28	“ Micro-sections of oolitic structures.....	780

FIGURES

HOPKINS:

Figure 1—Sketch map of a portion of eastern central New York..	69
--	----

MOORE:

Figure 1—Thin-sections of oolitic and pisolitic barite.....	78
---	----

CAIRNES :	Page
Figure 1—Sketch map showing Yukon-Alaska International boundary line.....	181
WRIGHT :	
Figure 1—Section of Don Valley brickyard, Toronto.....	206
“ 2—Map showing stages of recession of the North American ice-sheet	207
“ 3—Map of North American Pleistocene ice-sheet at its maximum extension.....	212
WRIGHT :	
Figure 1—Map of the vicinity of Warren, Pennsylvania.....	216
SCHUCHERT :	
Figure 1—Paleogeography of Medina, Cataract, and Brassfield seas.	294
BROWN :	
Figure 1—Formations sectioned by the Red Deer River between Red Deer and the mouth of Sand Creek, with location of important fossils in the American Museum collection	360
“ 2—Horizontal section of Red Deer River canyon between Red Deer and mouth of Sand Creek.....	363
MATTHEW :	
Figure 1—Geologic range of land vertebrates in typical American continental formations of late Cretaceous and Tertiary time	387
“ 2—Approximate correlations of typical formations of the late Cretaceous and early Tertiary in Europe and western America based on their vertebrate faunas....	393
“ 3—Division between Cretaceous and Tertiary periods, as indicated by terrestrial vertebrate faunæ of typical western formations.....	398
OSBORN :	
Figure 1—Phylogeny of the titanotheres as known to December, 1913	404
OSBORN :	
Figure 1—First and last known stages in the evolution of the titanotheres	406
OSBORN :	
Figure 1—Restoration of mastodon and elephants.....	408
“ 2—Restoration of elephants.....	409
WARREN and POWERS :	
Figure 1—Map of Diamond Hill-Cumberland Hill region.....	437
“ 2—Geological section through Copper Mine Hill.....	469
“ 3—Geological section through Cumberland Hill.....	471
HUNTINGTON :	
Figure 1—Solar heat, sun-spots, terrestrial temperature, and volcanoes	484
“ 2—Growth of trees at Eberswalde, Germany, and sun-spots.	495
“ 3—Storm tracks in the United States.....	498
“ 4—Storm tracks in Europe.....	500

HUNTINGTON :

Page

Figure 5—Storminess during the sun-spot maximum of 1892-1894 compared with that of the sun-spot maximum of 1888-1890	504
“ 6—Storminess during the sun-spot maximum of 1905-1907 compared with the minimum of 1900-1902.....	505
“ 7—Average storminess of 9 years of sun-spot maxima compared with 12 years of sun-spot minima between 1877 and 1912.....	506
“ 8—Comparative storminess of North America during the sun-spot cycles of 1889-1900 and 1901-1911.....	508
“ 9—Storms and sun-spots in the main American area of storm-shifting, according to Kullmer's law.....	512
“ 10—Comparative storminess of Europe during the sun-spot maximum of 1882-1884 and the minimum of 1877-1879.	516
“ 11—Comparative storminess of Europe during the sun-spot maximum of 1882-1884 and the minimum of 1888-1890.	518
“ 12—Comparative storminess of Europe during periods of maximum and minimum sun-spots.....	520
“ 13—Changes of climate in California and in western and central Asia.....	530
“ 14—Changes in California climate for 2,000 years, as measured by growth of sequoia trees.....	530
“ 15—Historic changes in precipitation.....	542
“ 16—Comparative storminess of 9 years of maximum sun-spots and 12 years of minimum sun-spots in the United States in percentages of mean storminess for 30 years.....	545
“ 17—Comparative precipitation of 9 years of maximum sun-spots and 9 years of minimum sun-spots in percentages of the mean precipitation.....	546
“ 18—Major and minor sun-spot cycles.....	554
“ 19—The double storm belt of the United States.....	570
“ 20—The distribution of loess—its relation to Quaternary glaciation and to present deserts and subarid regions.	575
“ 21—Cloudiness in regions having various temperature anomalies, according to Table 7.....	582
“ 22—Temperature anomalies for various degrees of cloudiness, according to Table 8.....	583
“ 23—Glaciation and the distribution of land and sea during the Permian era.....	586

LEWIS :

Figure 1—Geological cross-section of First Watchung Mountain....	626
“ 2—Diagrammatic cross-section at Glenside Park, New Jersey	628

BROWN :

Figure 1—Diagrammatic reproductions of oolitic structure.....	763
“ 2—Graphic summary of mineralogie changes in ores.....	772

(28 plates; 47 figures.)

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Vol. 2, 1890.....	622 + xiv	23	63
Vol. 3, 1891.....	541 + xi	17	72
Vol. 4, 1892.....	458 + xi	10	55
Vol. 5, 1893.....	655 + xii	21	43
Vol. 6, 1894.....	528 + x	27	40
Vol. 7, 1895.....	558 + x	24	61
Vol. 8, 1896.....	446 + x	51	29
Vol. 9, 1897.....	460 + x	29	49
Vol. 10, 1898.....	534 + xii	54	83
Index to volumes 1-10.....	209	..	..
Vol. 11, 1899.....	651 + xii	58	37
Vol. 12, 1900.....	538 + xii	45	28
Vol. 13, 1901.....	583 + xii	58	47
Vol. 14, 1902.....	609 + xii	65	43
Vol. 15, 1903.....	636 + x	59	16
Vol. 16, 1904.....	636 + xii	94	74
Vol. 17, 1905.....	785 + xiv	84	96
Vol. 18, 1906.....	717 + xii	74	59
Vol. 19, 1907.....	617 + x	41	31
Vol. 20, 1908.....	749 + xiv	111	35
Index to volumes 11-20.....	422	..	..
Vol. 21, 1909.....	823 + xvi	54	109
Vol. 22, 1910.....	747 + xii	31	66
Vol. 23, 1911.....	758 + xvi	43	44
Vol. 24, 1912.....	737 + xviii	36	60
Vol. 25, 1913.....	802 + xviii	28	47

PARTS OF VOLUME 25

	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Number 1.....	1-204	1-8	3	\$2.30	\$3.45
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REPRINTS FROM VOLUME 25

REPRINTS.	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Proceedings of the Twenty-sixth Annual Meeting of the Geological Society of America, held at Princeton, New Jersey, December 30 and 31, 1913, and January 1, 1914. E. O. HOVEY, <i>Secretary</i> .	1-118	1-3	2	\$1.25	\$1.85
Proceedings of the Fourteenth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, April 11 and 12, 1913. GEORGE D. LOUDERBACK, <i>Secretary</i>	119-126	....	....	.10	.15
Proceedings of the Fifth Annual Meeting of the Paleontological Society, held at Princeton, New Jersey, December 31, 1913, and January 1, 1914. R. S. BASSLER, <i>Secretary</i>	127-156	....	....	.30	.45
Pioneers in coastal plain geology. E. A. SMITH.....	157-178	....	....	.20	.30
Geological section along the Yukon-Alaska boundary line between Yukon and Porcupine Rivers. D. D. CAIRNES.....	179-204	4-8	1	.40	.60
Age of the Don River glacial deposits, Toronto, Ontario. G. F. WRIGHT.....	205-214	....	1-3	.15	.20
Evidence of a glacial dam in the Allegheny River between Warren, Pennsylvania, and Tionesta. G. F. WRIGHT.....	215-218	9	1		
Pleistocene submergence of the Connecticut and Hudson valleys. H. L. FAIRCHILD.....	219-242	10-11	....	.30	.45
Magmatic differentiation and assimilation in the Adirondack region. W. J. MILLER.....	243-264	....	....	.20	.30
Characteristics of a corrosion conglomerate. F. W. SARDESON....	265-276	12	....	.15	.20
Medina and Cataract formations of the Siluric of New York and Ontario. C. SCHUCHERT†.....	277-320	13-14		.50	.75

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Cretaceous-Tertiary boundary in the Rocky Mountain region. F. H. KNOWLTON†.....	325-340			.15	.20
Boundary between Cretaceous and Tertiary in North America as indicated by stratigraphy and in- vertebrate faunas. T. W. STAN- TON†.....	341-354	....	....	.15	.20
Cretaceous Eocene correlation in New Mexico, Wyoming, Mon- tana, Alberta. B. BROWN†..	355-380	....	1-2	.25	.35
Evidence of the Paleocene verti- brate fauna on the Cretaceous- Tertiary problem. W. D. MAT- THEW†.....	381-402	....	1-3	.20	.30
Recent results in the phylogeny of the Titanotheres. H. F. OSBORN†	403-405	....	....	.15	.20
New Methods of restoring <i>Eoti-</i> <i>tanops</i> and <i>Brontotherium</i> . H. F. OSBORN†.....	406	....	1		
Restoration of the world series of elephants and mastodons. H. F. OSBORN†.....	407-410	....	1-2		
Rectigradations and allometrons in relation to the conceptions of the "Mutations of Waagen" of spe- cies, genera, and phyla. H. F. OSBORN†.....	411-416				
Geology of the Uinta formation. E. DOUGLASS†.....	417-420			.10	.15
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Geology of the Diamond Hill- Cumberland District in Rhode Island-Massachusetts C. H. WARREN and SIDNEY POWERS...	435-476		1-3	.40	.60
The solar hypothesis of climatic changes. E. HUNTINGTON.....	477-590	....	1-23	1.15	1.70
Origin of pillow lavas. J. V. LEWIS.	591-654	15-25	1-2	.95	1.45
Mechanical composition of clastic sediments. J. A. UDDEN.....	655-744			.90	1.35
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CORRECTIONS AND INSERTIONS

All contributors to volume 25 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

Page 341, line 12 from top; *for* "Evolution" *read* Evidence.

" 347, line 3 from top; *for* "EVOLUTION" *read* EVIDENCE.

" 440, line 17 from top; *omit* "Permean."

" 460, line 2 from bottom; *for* "Torbrook, Nictaux" *read* Torbrook and Nictaux.

BULLETIN

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Geological Society of America

VOLUME 25 NUMBER 1

MARCH, 1914



JOSEPH STANLEY-BROWN, EDITOR

PUBLISHED BY THE SOCIETY
MARCH, JUNE, SEPTEMBER, AND DECEMBER

CONTENTS

	Pages
Proceedings of the Twenty-sixth Annual Meeting of the Geological Society of America, held at Princeton, New Jersey, December 30 and 31, 1913, and January 1, 1914. E. O. Hovey, Secretary - - - - -	1-118
Proceedings of the Fourteenth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, April 11 and 12, 1913. G. D. Louderback, Secretary - - - - -	119-126
Proceedings of the Fifth Annual Meeting of the Paleontological Society, held at Princeton, New Jersey, December 31, 1913, and January 1, 1914. R. S. Bassler, Secretary - - - - -	127-156
Pioneers in Gulf Coastal Plain Geology. Presidential Address by Eugene A. Smith - - - - -	157-178
Geological Section Along the Yukon-Alaska Boundary Line between Yukon and Porcupine Rivers. By D. D. Cairnes - - - - -	179-204

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OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT
PRINCETON, NEW JERSEY, DECEMBER 30 AND 31, 1913,
AND JANUARY 1, 1914.

EDMUND OTIS HOVEY, *Secretary*

CONTENTS

	Page
Session of Tuesday, December 30.....	4
Election of Auditing Committee.....	5
Election of officers.....	5
Election of Fellows.....	6
Memorial of William M. Fontaine; by T. L. Watson.....	6
Memorial of Thomas Moore Jackson; by I. C. White.....	13
Events leading up to the organization of the Geological Society of America; by J. J. Stevenson.....	15
Review of the early history of the Society; by Herman L. Fairchild..	17
History of the Bulletin; by J. Stanley-Brown.....	24
Review of the formation of geological societies in the United States; by N. H. Winchell.....	27
Titles and abstracts of papers presented in general session and dis- cussions thereon.....	30
Mechanics of formation of arcuate mountains [abstract]; by W. H. Hobbs.....	30
Early Tertiary glaciation in the San Juan region of Colorado [ab- stract and discussion]; by Wallace Walter Atwood.....	31
Origin of pillow lavas [abstract and discussion]; by J. Volney Lewis..	32
Titles and abstracts of papers presented before the First Section and discussions thereon.....	33
Earthquake sea waves [abstract and discussion]; by Harry Fielding Reid.....	33
Recent earthquakes in Panama and their causes; by Donald F. Mac- Donald.....	34
Criticism of the Hayfordian conception of isostasy regarded from the standpoint of geology [abstract]; by W. H. Hobbs.....	34
Earth-movements in the Minnesota portion of the Lake Agassiz basin during and since the lake occupancy [abstract and discussion]; by Frank Leverett.....	34
Time measures in the Niagara Gorge and their application to Great Lake history [abstract and discussion]; by Frank B. Taylor.....	35
Illustration of intraformational corrugation [abstract and discus- sion]; by John M. Clarke.....	37

	Page
Illustrations of the recent exposure of the Saratoga Springs [abstract]; by John M. Clarke.....	38
An alternative explanation of the origin of the Saratoga mineral waters [abstract and discussion]; by R. Ruedemann.....	38
Titles and abstracts of papers presented before the Second Section and discussions thereon.....	39
Characteristics of a corrosion conglomerate [abstract]; by F. W. Sardeson.....	39
A pre-Cambrian unconformity in Vermont [abstract]; by Arthur Keith.....	39
Reconnaissance of the Algonkian rocks of southeast Newfoundland [abstract]; by Arthur Buddington.....	40
Sections illustrating the lower part of the Silurian system of southwestern Ontario [abstract]; by Merton Y. Williams.....	40
Evidence of climatic oscillations in the Permo-Carboniferous beds of Texas [abstract]; by E. C. Case.....	41
Geologic history of the Florida coral-reef tract and comparisons with other coral-reef areas [abstract]; by Thomas Wayland Vaughan ...	41
Titles and abstracts of papers presented before the Third Section and discussions thereon.....	43
Graphic method of representing the chemical relations of a petrographic province [abstract and discussion]; by Frank D. Adams....	43
Effusive and intrusive in the quantitative classification [abstract]; by Alfred C. Lane.....	43
Change in the crystallographical and optical properties of quartz with rise in temperature [abstract and discussion]; by Fred E. Wright..	44
Mode of formation of certain gneisses in the highlands of New Jersey [abstract and discussion]; by C. N. Fenner.....	44
Magmatic differentiation and assimilation in the Adirondack region [abstract and discussion]; by William J. Miller.....	45
New point in the geology of the Adirondacks [abstract and discussion]; by J. F. Kemp.....	47
Minerals from the ore deposits at Park City, Utah [abstract and discussion]; by Frank R. Van Horn.....	47
Deepest boring in West Virginia [abstract]; by I. C. White.....	48
Presidential address: Pioneers in Gulf Coastal Plain geology; by E. A. Smith.....	48
Session of Wednesday, December 31.....	48
Report of Committee on Photographs.....	48
Report of Committee on Geological Nomenclature.....	49
Report of Auditing Committee.....	49
Amendment to the By-Laws.....	49
Bibliography of formation names.....	50
Report of the Council.....	51
Secretary's report.....	51
Treasurer's report.....	53
Editor's report.....	56
Title and abstracts of papers presented in general session and discussions thereon.....	58

	Page
Improvements in methods of investigating highly carbonized materials and their bearing on the mode of deposition of coal [abstract]; by Edward Charles Jeffrey.....	58
Origin of oolites and the oolitic texture in rocks [abstract and discussion]; by Thomas Clachar Brown.....	58
Precise leveling and the problem of coastal subsidence [abstract and discussion]; by Douglas W. Johnson.....	59
Some historical evidence of coastal subsidence in New England [abstract and discussion]; by Charles A. Davis.....	61
Pleistocene marine submergence of the Connecticut and Hudson valleys [abstract and discussion]; by Herman L. Fairchild.....	63
Titles and abstracts of papers presented before the First Section and discussion thereon.....	65
Cause of the postglacial deformation of the Ontario region [abstract and discussion]; by J. W. Spencer.....	65
Origin of dolomite [abstract]; by Francis M. Van Tuyl.....	66
Flattening of limestone gravel boulders by solution; by Johan August Udden.....	66
High-level loop channel [abstract]; by T. C. Hopkins.....	68
Divergent ice-flow on the plateau northeast of the Catskill Mountains as revealed by ice-molded topography; by John L. Rich.....	68
Length and character of the earliest interglacial beds [abstract]; by A. P. Coleman.....	71
Age of the glacial deposits in the Don Valley, Toronto, Ontario [abstract]; by G. Frederick Wright.....	71
Titles and abstracts of papers presented before the Third Section and discussions thereon.....	73
Manganese deposits of Conception and Trinity bays, Newfoundland [abstract]; by Nelson C. Dale.....	73
Geology of the Wabana iron ore of Newfoundland [abstract]; by Albert O. Hayes.....	74
Geology of the Cumberland-Diamond Hill district, Massachusetts-Rhode Island [abstract]; by Charles H. Warren and Sidney Powers.....	75
Sedimentary character of garnetiferous hornblende schist, Hanover, New Hampshire [abstract]; by John Wesley Merritt.....	75
Oolites of the Chimneyhill formation, Oklahoma [abstract and discussion]; by Chester A. Reeds.....	75
Temiskamite, a new nickel arsenide from Ontario [abstract]; by T. L. Walker.....	76
Oolitic and pisolitic barite from the Saratoga oil field, Texas; by E. S. Moore.....	77
Annual dinner.....	80
Session of Thursday, January 1.....	80
Some observations of the Volcano Kilauea in action [abstract]; by Arthur L. Day.....	80
Titles and abstracts of papers presented in general session and discussions thereon.....	81
Stratigraphy of Red Beds of New Mexico [abstract and discussion]; by N. H. Darton.....	81

	Page
Solar hypothesis of climatic changes [abstract]; by Ellsworth Huntington.....	82
Vote of thanks.....	83
Titles and abstracts of papers presented before the First Section and discussions thereon.....	84
Occurrence of glacial drift on the Magdalen Islands [abstract]; by J. W. Goldthwait.....	84
Evidence of a glacial ice-dam in the Allegheny River between Warren, Pennsylvania, and Tionesta, Pennsylvania [abstract]; by G. Frederick Wright.....	84
Preglacial Miami and Kentucky rivers [abstract and discussion]; by N. M. Fenneman.....	85
Delaware terraces [abstract]; by N. H. Winchell.....	86
Sublacustrine glacial erosion in Montana [abstract]; by William M. Davis.....	86
Glacial Lake Missoula [abstract]; by R. W. Stone.....	87
Physiographic relations of serpentine, with special reference to the serpentine stock of Staten Island, New York [abstract and discussion]; by William Otis Crosby.....	87
Erosive potential of desert waters [abstract]; by Charles R. Keyes...	88
Submarine topography in Glacier Bay, Alaska [abstract]; by Lawrence Martin.....	88
Buried gorge of the Hudson River and geologic relations of Hudson syphon of the Catskill Aqueduct [abstract]; by W. O. Crosby.....	89
Abstract of papers presented before the Third Section and discussion thereon.....	90
Composition of bornite and its relation to other sulfominerals [abstract and discussion]; by Edward H. Kraus.....	90
Genesis of glauconite [abstract]; by Chase Palmer.....	91
Crystallization of certain pyroxene-bearing artificial melts [abstract]; by N. L. Bowen.....	91
Physical-chemical system, lime-alumina-silica and its geological significance [abstract]; by Fred E. Wright and G. A. Rankin.....	92
Constitution and By-Laws.....	93
References to adoption and changes.....	93
Constitution.....	93
By-Laws.....	97
Publication rules of the Geological Society of America.....	101
Register of the Princeton Meeting, 1913.....	105
Officers, Correspondents, and Fellows of the Geological Society of America.	107

SESSION OF TUESDAY, DECEMBER 30

The first general session of the Society was called to order at 9.50 o'clock a. m., Tuesday, December 30, at Guyot Hall, Princeton University, Princeton, New Jersey, by President Smith, who introduced Prof.

W. B. Scott, who in turn welcomed the visiting geologists in the name of Princeton University.

In the absence of the printed Council report, which had been delayed in transit, the Treasurer presented his annual report from manuscript.

ELECTION OF AUDITING COMMITTEE

The Auditing Committee, consisting of E. B. Mathews, U. S. Grant, and T. W. Vaughan, was then elected, and the Treasurer's report was referred to it.

ELECTION OF OFFICERS

The Secretary declared the vote for officers for 1914 as follows, the ballots having been canvassed and counted by the Council in accordance with the By-Laws:

President:

GEORGE F. BECKER, Washington, D. C.

First Vice-President:

WALDEMAR LINDGREN, Boston, Mass.

Second Vice-President:

HORACE B. PATTON, Golden, Colo.

Third Vice-President:

HENRY FAIRFIELD OSBORN, New York City.

Secretary:

EDMUND OTIS HOVEY, New York City.

Treasurer:

WILLIAM BULLOCK CLARK, Baltimore, Md.

Editor:

JOSEPH STANLEY-BROWN, New York City.

Librarian:

FRANK R. VAN HORN, Cleveland, Ohio.

Councilors:

R. A. F. PENROSE, JR., Philadelphia, Pa.

W. W. ATWOOD, Cambridge, Mass.

ELECTION OF FELLOWS

The Secretary announced the election in due form of the following Fellows, the ballots having been canvassed and counted by the Council:

ROLLIN THOMAS CHAMBERLIN, S. B., Ph. D., University of Chicago, Chicago, Ill.

CLARENCE EVERETT GORDON, B. S., A. M., Ph. D., Massachusetts Agricultural College, Amherst, Mass.

LOUIS C. GRATON, B. S., Harvard University, Cambridge, Mass.

CHRIS A. HARTNAGEL, B. S., Ph. D., M. A., State Museum, Albany, N. Y.

MIGUEL A. R. LISBOA, Director Irrigation and Water Supply Service, Rio de Janeiro, Brazil.

G. A. F. MOLENGRAAF, Technical High School, Delft, Holland.

CHESTER A. REEDS, B. S., M. S., Ph. D., American Museum of Natural History, New York, N. Y.

MIGNON TALBOT, A. B., Ph. D., Mount Holyoke College, South Hadley, Mass.

ARTHUR C. TROWBRIDGE, B. S., Ph. D., State University of Iowa, Iowa City, Iowa.

WILLIAM HENRY TWENHOFEL, B. A., M. A., Ph. D., University of Kansas, Lawrence, Kans.

JOSEPH B. UMPLEBY, A. B., M. S., Ph. D., U. S. Geological Survey, Washington, D. C.

CHARLES E. WEAVER, B. S., Ph. D., University of Washington, Seattle, Wash.

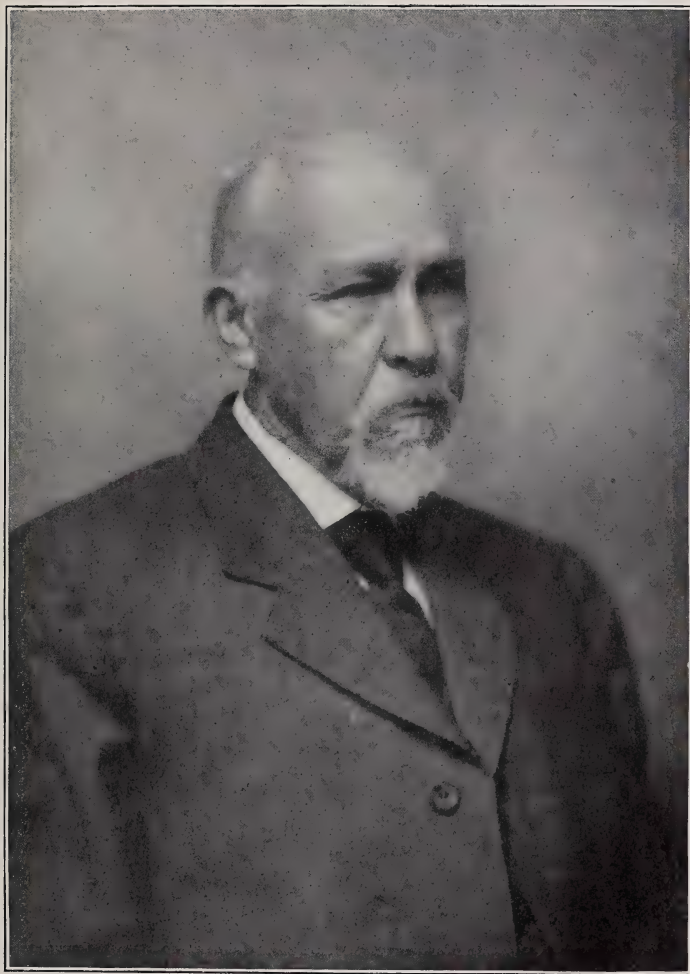
Announcement was then made that the Society had lost one Fellow by death during the year 1913: W. M. Fontaine, and one Correspondent, Herman Credner. A memorial of the deceased Fellow was presented as follows:

MEMORIAL OF WILLIAM M. FONTAINE

BY THOMAS L. WATSON

Professor Fontaine, who for thirty-two years (1879-1911) was Corcoran Professor of Natural History and Geology in the University of Virginia, died suddenly at his home at the university on April 30, 1913, in his seventy-eighth year. Though of an advanced age, he was apparently in good health and was no less active mentally and physically at the time of his demise than for several years previous. His passing away was entirely unexpected, and his sudden death brought forth expressions of the deepest sympathy and regret from the entire university community.

It is of more than passing interest that the subject of this sketch and Prof. Lester F. Ward, collaborators and both distinguished for investigations in the field of paleobotany, should have died within a few weeks of



Wm M. Fontaine

each other. The passing of Professors Fontaine and Ward removed the last two of a small but distinguished group of eminent pioneers in the field of fossil botany.

After faithful and distinguished service as teacher for thirty-two years in his alma mater, during which he achieved wide reputation for scholarly contributions in his chosen field of geology, Professor Fontaine was retired September 1, 1911, on the Carnegie Foundation for the Advancement of Teaching.

Professor Fontaine was born in Louisa County, Virginia, on December 1, 1835, the son of James and Juliet (Morris) Fontaine, representatives of old and distinguished families in the State. He was of Huguenot descent on his paternal side, a lineal descendant of Jean de la Fontaine, who was martyred at La Mans, France, in 1561. His paternal ancestor came to Virginia with other refugees from the western provinces of France which border on the Atlantic, where they might be free to live and practice "the Huguenot ideals of civil and religious liberty, which they fought for in France and taught in Virginia."

Young Fontaine grew up on his father's plantation, and was prepared for college under the instruction of a private tutor, Richard Maury, and at Hanover Academy. He entered the University of Virginia in 1856, at the age of twenty-one, and was graduated with the Master of Arts degree in 1859. Following his graduation from the University of Virginia, he taught in Hanover Academy in 1860-1861. At the outbreak of the Civil War he joined the Confederate Army, in which he served as Second Lieutenant of Artillery, until 1862; then as First Lieutenant of Ordnance till April 9, 1865. The years 1865 to 1868 were spent partly in teaching school and partly in farming.

In 1869 and 1870 he was a student at the Royal School of Mines, Freiburg, Saxony. In 1873 he was elected professor of chemistry and geology in the University of West Virginia, in which capacity he served until 1879. In 1879 he was called to the Corcoran Chair of Natural History and Geology (established in 1878) and Curator of Brooks Museum at the University of Virginia, being its first incumbent, and in which capacity he ably served until September, 1911, when he retired on the Carnegie Foundation for the Advancement of Teaching. From the date of his retirement, in 1911, until that of his death, in 1913, Professor Fontaine continued to reside at the University during each academic session and, as was his custom for some years previous to retirement, spent the summers at his old home in Hanover County.

Immediately on his taking up his duties as professor in the University of Virginia, he became active in the geology of the State. Appreciating

the fact that a knowledge of geology was not to be gained from the lecture-room, but from study and observation in the field, Professor Fontaine, on his recommendation to the Rector and Visitors of the University, was authorized to close the lecture work in geology on the last day of April in each year and devote the remainder of the session to work in the field with his students. For the conduct of this work an appropriation defraying the necessary field expenses of himself and class was granted by the University Board of Control.

By thus devoting a part of each session and the summers to field work, he accomplished a great deal of valuable work in all parts of the State. His activity in this direction, extending over many years, is very forcibly shown in the large number of field notebooks on file in the Department of Geology in the University of Virginia. Unfortunately, the results of his work were only partly published; much the greater share of his notes were never worked into shape for publication.

Numerous published papers in scientific journals and in publications of the United States Geological Survey and the United States National Museum (see bibliography) are testimonials of the excellent work accomplished by him. These show a wide range of subjects treating of various aspects of geology, mineralogy, and fossil botany. It was in the latter field of investigation (paleobotany), more especially Mesozoic fossil botany, however, that his most valuable contributions to science were made and which won for him distinction in this country and abroad.

Dr. F. H. Knowlton, of the United States National Museum and Geological Survey, distinguished for his contributions to fossil botany, very kindly furnished the following sketch of the paleobotanical work of Professor Fontaine:

"Professor Fontaine's most notable contributions to American science were in the field of paleobotany, in which he was a more or less active factor for almost a third of a century, namely, from 1874 to 1905. His first papers, written while professor of physics and chemistry in the University of West Virginia, were largely of a geological nature, dealing especially with the coal-bearing Paleozoic section along New River, West Virginia, which he believed to be of Devonian age—a view, however, which subsequent workers in the field have not sustained. His use of fossil plants in these studies was comparatively slight, and his error in their interpretation was obviously due to inadequate material for comparison and lack of suitable library facilities. His most important work in the Paleozoic field was a joint production with Dr. I. C. White on 'The Permian or Upper Carboniferous Flora of West Virginia and S. W. Pennsylvania,' issued in 1880. This forms a compact volume of nearly 150 pages and 38 plates, published by the Second Geological Survey of Pennsylvania. This was valuable pioneer work and laid the foundation of much subsequent investigation.

"If Professor Fontaine had remained in West Virginia, he doubtless would have extended his work in the Paleozoic floras, but in 1878 he became professor of geology in the University of Virginia, and thereafter his studies were confined to the Mesozoic floras, the materials for which were at hand. In 1879 he published his first paper on the Mesozoic of Virginia, the materials for which he had been gathering during the summer vacations for a number of years previously. This was a preliminary account, dealing largely with the geology and areal distribution of the plant beds of the earlier Mesozoic; or, as it became later to be called, the *Older Mesozoic of Virginia*. Very brief mention was also made at this time of the richly plant-bearing clays of the *Younger Mesozoic*, or Potomac Group.

"The full report on the older flora was issued in 1883, as volume 6 of the monographs of the United States Geological Survey, under the title 'Contributions to the Knowledge of the Older Mesozoic Flora of Virginia.' In this he presented the full and elaborate description of the flora of the Richmond coal basin, which has furnished the most complete and best preserved of American Triassic floras. This became at once the standard work of reference on its subject and did much to stimulate investigation by others in beds of similar age, notably in Pennsylvania.

"During the succeeding five or six years Professor Fontaine was engaged in collecting and studying what had developed into the rich and varied flora of the so-called Younger Mesozoic of Virginia and Maryland. The results were published in 1889 under the title 'The Potomac or Younger Mesozoic Flora,' being volume 15 of the monographs of the United States Geological Survey. In a number of ways this was an epoch-marking work, for to Professor Fontaine belongs the honor of having described the oldest angiospermous flora known. Previous to this work the oldest dicotyledonous flora recognized in this country was that of the Dakota Group, but this discovery extended the range from the lower part of the Upper Cretaceous to near the base of the Lower Cretaceous. The Potomac flora contained descriptions of 365 species, of which a number were obviously dicotyledons. As might be presumed, many of these were exceedingly archaic in appearance, though subsequent study of later and better preserved material appears to indicate that they were somewhat less archaic than was at first supposed; in fact, it is apparent that, although this was a long step backward, we are still far from the actual point of origin of the group.

"By the publication of the two works mentioned above, Professor Fontaine became the recognized authority on the Mesozoic floras of the eastern portion of the United States, and it was but natural that he should be called on to extend his studies to include floras of similar age in other parts of the country. In succession he published descriptive reports on the Kootenai of Montana (1891, 1892), the Trinity of Texas (1893), and the Shasta of California (1894), all of which he found more or less closely related to those of Virginia and adjacent States. Many of these studies were undertaken at the suggestion of the late Lester F. Ward, who about this time (1895) projected a series of critical reviews of the Mesozoic floras of the United States. Professor Ward collected the material which was sent to Fontaine for study and description, and in this way a great mass of interesting and valuable data were secured. The first of these reports, published in 1900, began with a critical review of

all known Triassic floras in the United States, to which Fontaine contributed studies in the newly discovered Pennsylvania plant-bearing deposits (this in cooperation with A. Wanner) and a review of the types of the Ebenezer Emmons collections from the coal field of North Carolina, which had been found in the museum of Williams College. The review of the Mesozoic flora was begun, and to this Fontaine supplied the study of the floras from California and Oregon, then recently discovered.

"The second installment of Ward's *Status of the Mesozoic Floras* was published in 1905, and to which Fontaine contributed the major portion of the technical studies of the floras. This contained a continuation of the Jurassic flora of Oregon and brief accounts of a number of small collections from Alaska, California, and Montana. In this paper there was inaugurated the review of the Lower Cretaceous floras, Fontaine supplying reports on the Shasta flora of California, the Kootenai of Montana, and the Lakota of Wyoming. It also included an extensive review and revision of the Potomac flora, especially as developed from many newly discovered localities in Virginia and Maryland. This completed Fontaine's active work in fossil plants.

"Professor Fontaine's paleobotanical work is thus seen to have been extensive and varied. As a pioneer worker he will take rank with Lesquereux, Newberry, and Ward, each of whom made some field his own, and combined they laid the foundations on which all subsequent work in this country must be grounded. Although Fontaine evidently lacked adequate training in modern botanical methods, his work was, on the whole, careful and painstaking. He was keen and critical in his discrimination of forms, though, as so frequently happens in the work of a pace-maker in a new field, subsequent larger and better preserved collections have shown that in some cases too many forms were accorded specific standing. Whatever may be the fate of certain of his systematic determinations, as a whole, Fontaine's work will stand out as of the highest importance and value, not only in the field of paleobotany, but in its application to the broader field of stratigraphic geology."

Professor Fontaine was elected a Fellow of the Geological Society of America in December, 1888, which connection was maintained till his death, and was a member of the Huguenot Society of America.

Personally Professor Fontaine was of a modest and retiring disposition, kind and generous to a fault; quiet and unassuming, but dignified; always shrinking from publicity. Those of his friends who knew him best were devoted to him not only through admiration for his large intellectuality, but through devotion for his great traits of character. He was never married.

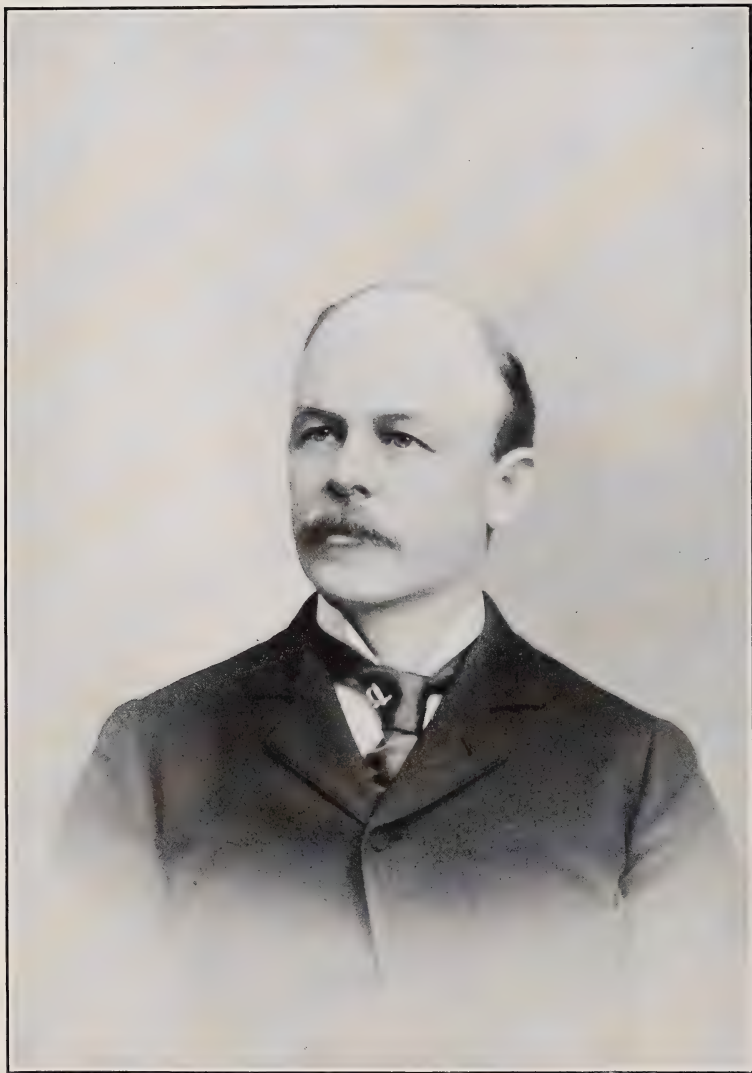
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J. M. Jackson

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MEMORIAL OF THOMAS MOORE JACKSON

BY I. C. WHITE¹

Thomas Moore Jackson, C. E., D. Sc., of Clarksburg, West Virginia, the son of James Madison Jackson and Caroline Moore Jackson, was elected a Fellow of this Society May 20, 1889, and died February 3, 1912, in his sixtieth year. He graduated from the engineering department of Washington and Lee University in June, 1873, with the degree of C. E., and the same institution conferred on him the degree of D. Sc. in 1887. After his graduation he engaged in the engineering pursuits of railway and coal mining work until his election to the Chair of Civil and Mining Engineering in the West Virginia University in 1887.

As a teacher of engineering, Professor Jackson was intensely practical, encouraging his students to combine theory with actual work on engineering projects, so that the men who graduated under his tutelage stepped immediately from the University into good engineering positions, in which all have achieved distinction. It was while at the West Virginia University that Professor Jackson and his pupils ran the lines of levels on coal beds under the direction of the writer, by which the latter was enabled to locate the Mannington oil field in Marion County, West Virginia, 35 miles in advance of any developments, and to demonstrate conclusively to the oil and gas fraternity the reliability of the "Anticlinal Theory" as described in the Bulletin of this Society.²

Professor Jackson resigned from the Chair of Civil and Mining Engineering in the State University in June, 1891, to engage in the more active field work of his profession, constructing, in connection with the late H. H. Rogers, of Standard Oil fame, the "Short Line" Railway from Clarksburg to New Martinsville in order to give his home city a

¹ Presented orally in abstract at the New Haven meeting of the Society, but the manuscript was not received in time for insertion in its proper place in volume 24.

² I. C. White: The Mannington oil field and the history of its development, vol. 3, pp. 187-216.

competing outlet independent of the Baltimore and Ohio system, an object to which he had devoted many years of his busy life. But soon after the completion of the railway, and in a moment of seeming realization of his life's work, Mr. Rodgers, who controlled the stock of the "Short Line" Railway, as well as that of its connection, the Ohio River Railway, sold both to the Baltimore and Ohio Railroad, to the great discomfiture and financial loss of his too confiding friend, Professor Jackson. Descended from the same stock and a near kinsman of the intrepid Confederate leader, Stonewall Jackson, obstacles and disappointments, which would have completely crushed the spirit of the ordinary man, appeared only to spur Professor Jackson to still more determined effort to persevere in the work he had undertaken, and hence the last year of his life was given to the task of building a new and independent line of railway to connect the city of his birth with the outside world, and it was during the inspection of its construction, in company with the contractor, on an inclement day, on February 1, 1912, that he contracted an illness that resulted in his sudden demise only two days later. As a man and citizen he was greatly esteemed and beloved by his neighbors and acquaintances.

Professor Jackson was well born. His great-grandfather, George Jackson, was a Representative in the 4th, 6th, and 7th Congresses of the United States, while his grandfather, John G. Jackson, was a brother-in-law of President Madison, his marriage to Mary Payne, the sister of Dolly Madison, having been the first one in the White House. He was also a Representative in the 8th, 9th, 10th, 11th, 13th, and 14th Congresses, and in 1819 was appointed by President Monroe judge of the United States Court for the Western District of Virginia, which position he held until his death. Judge John G. Jackson's first wife, Mary Payne Jackson, died February 13, 1808, and is buried in Clarksburg, West Virginia, alongside of her mother, Mrs. Payne, the mother of Dolly Madison.

In 1810 Judge John G. Jackson married his second wife, Mary S. Meigs, the daughter of Return Jonathan Meigs, who was Postmaster General under President Madison and twice Governor of Ohio. This second wife was the grandmother of Thomas Moore Jackson and mother of James Madison Jackson, his father, who was a first cousin of Thomas J. Jackson, the celebrated Confederate general, Stonewall Jackson.

Professor Jackson, although taking great interest in all scientific matters, was of such a modest and retiring disposition that he could never be induced to prepare any formal papers for publication, and hence he will be remembered more by his active work in the field than by any published writings.

Professor Jackson, whose father, mother, and twin sister preceded him

to the grave, was married in 1884 to Miss Emma Lewis, daughter of the late Judge and Mrs. C. S. Lewis, who, with his only child, Miss Florrie, survive him.

The Secretary then read appreciative letters from W. Kilian and J. J. H. Teall accepting their election as Correspondents of the Society, and made several announcements with regard to the program and the events of the meeting.

This being the twenty-fifth anniversary of the first meeting of the Society, the following three papers were read in commemoration of the event:

*EVENTS LEADING UP TO THE ORGANIZATION OF THE GEOLOGICAL SOCIETY
OF AMERICA*

BY J. J. STEVENSON

The Geological Society of America was formed of necessity. The American Association for the Advancement of Science was at first an association of geologists, who had discovered the need of closer fellowship in those days of small incomes and high rates of postage. The naturalists, who suffered under the same limitations, urged the intimacy of relation between their work and geology, and they were admitted to membership in the society, which assumed the title, Association of Geologists and Naturalists. Men in other departments of scientific work, observing the advantages of personal contact, clamored for admission. Within a few years the organization developed into the American Association for the Advancement of Science, and geology was relegated to a subordinate place. The conditions, however, were advantageous. There were few men of science in the country and the members in attendance at meetings were not large; there was full opportunity for discussion and conference, with the added advantage that all were compelled to recognize the unity of scientific work. But after the Civil War everything was changed. The extraordinary expansion in several great industries awakened a popular interest in scientific matters, and within a few years the character of the Association was changed completely. It had increased greatly in numbers, the program of papers was crowded, and excursions became a portion of the work. Each year found less opportunity for discussion and conference and the Association no longer so useful to scientific workers as in the earlier days. The loss was felt especially by the geologists, who could not attend the summer meetings, and who felt that the great problems would not be solved properly unless those interested could discuss them fully and frankly. Some change was essential.

The matter assumed form in 1881 at the Association's Cincinnati meeting, where a committee, with N. H. Winchell as chairman and C. H. Hitchcock as secretary, was appointed to consider the advisability of forming a society of geologists. That committee reported at the next meeting, but the opposition was so strenuous that no action was taken. The effort was equally unsuccessful in 1883, and no further attempt was made until 1888. The obstacle was the Section of Geology and Geography in the Association, which had become

anything but a society of geologists, and this was to decide whether or not a geological society was needed. There was also a very well defined dread lest the organization of the Society might be an entering wedge leading to eventual disruption of the Association. The proposition was made that membership should be restricted to that of Section E and that the Association should choose the officers. These conditions were included in the call inviting American geologists to meet prior to the Cleveland meeting, in order to consider the formation of a geological society.

A large number of geologists came together at Cleveland on August 14, 1888. The difference in opinion was as marked as in previous meetings, but geologists were in the majority, and the decision was that the Society should be wholly independent of the Association, and that membership should be restricted to those actually engaged in field work or in teaching geology. It was agreed, however, that only members of Section E could be original members, while all others with the required qualifications would be eligible to election after formation of the Society. Those insisting on an independent organization urged, successfully, that the annual fee be fixed at \$10. They regarded this as important, believing that the cost would prevent all except geologists from claiming enrollment as original members. A committee, with Alexander Winchell as chairman and Edward Orton, C. H. Hitchcock, J. R. Proctor, and J. J. Stevenson as associates, was appointed to prepare a provisional constitution. The committee reported on the next day. The proposed constitution was adopted and the committee was continued, with authority to make all arrangements for formation of the Society.

A clause had been inserted that the Society should not be organized unless at least 100 persons agreed to become members. This was a wise suggestion, as it insured success from the beginning; but there were those who imagined that it was inserted to make failure certain, since it appeared impossible to secure the desired number at \$10 a year.

The committee placed the whole responsibility in the hands of its chairman and secretary. Prof. A. Winchell's facile pen prepared all the circular and Professor Stevenson stirred up geologists to a sense of their duty. Before leaving Cleveland the members of this subcommittee discussed fully the plan of procedure and decided that neither one would interfere with the other, and that no attention would be paid to suggestions from others; and this arrangement proved wholly satisfactory. In spite of all prognostications, the desired number was secured before the end of October, and the meeting of the organization was called for December 27, 1888, at Cornell University. At that meeting it was announced that 98 original Fellows had paid the fee and that 22 others had been chosen by the ballots of those Fellows; so that the Society was begun with an actual membership of 120.

The organizing meeting was merely formal. The important matters had been submitted to all the Fellows, and there remained little to be done beyond registering their discussion. Only 13 were present, of whom 7 are still with us. James Hall was chosen as the first president, Henry S. Williams as the treasurer, and John J. Stevenson as the secretary. A committee, with Joseph Le Conte as chairman and W J McGee as secretary, was appointed to consider the form of publication, and the Society adjourned, to meet at Toronto on August 28, 1889.

Thus was launched the new Society, dreaded as the wedge to work disintegration of science and of the American Association; but that Association has almost thrice as many members as it had 25 years ago. Other societies have been organized which, like our own, retain only a shadowy affiliation with the Association. Our Society has been of incalculable service to geologists. Prior to its organization there was little community of feeling, but abundance of personal antagonism. Misunderstandings arose because of isolation, which grew through correspondence into personal enmity; but that is of the past. In personal touch we have learned that we are all alike, each with many virtues and many frailties, and we have learned to judge ourselves more justly. The right of individual judgment is recognized and difference of opinion, even though extreme, no longer imperils personal friendship. Discussions at our meetings prove that the judicial temper prevails. In the former days men became more dogmatic as they advanced in age; now increasing years seem to bring with them increasing toleration for new conceptions.

The Society increased rapidly, so that at the end of the second year there were 203 Fellows and accumulation of a Permanent Fund had been begun. Mr. McGee, of the Advisory Committee on Publications, had been chosen as Editor, and the form proposed by him had been adopted. It proved so acceptable that it became the model. The older geologists, as well as those of the rising generation, gave generously of their time and strength, so that the Society's Bulletin became a standard publication, respected everywhere. The Secretary's work was that of rough-hewing. He was like one who excavates a cellar and lays a foundation. For one of his temperament, the duties were attractive only in part. The Society was new; the Fellows were not bound to it by tradition; some of them had an undue sense of importance and insisted on receiving much attention; the membership was scattered over the vast continent, and it was difficult to conceive means of convincing a far-off Fellow, who could not attend meetings, that he was as good as one living on the Atlantic coast. There were many who appeared to believe that the secretary was a lonely man and who sent him too many letters of advice, comfort, or expostulation, all of which had to be acknowledged with thanks for the kindly consideration. This burden of actual labor, which could not be transferred, with, in addition, the compulsory exhibition of patience and grateful courtesy, was too great for one already bearing much responsibility in other kinds of work. At the end of two years the executive staff was remodeled. Professor Fairchild became the secretary; Dr. I. C. White took charge of the finances; Mr. McGee retained the editorship for three years, when he was succeeded by Mr. Stanley-Brown. These men undertook the work of erecting the edifice, a house beautiful, its parts fitly bound together and standing foursquare. How they performed the work, you know. The inscription to Sir Christopher Wren in Saint Paul's Cathedral is for them also—"If you seek my monument, look around you."

REVIEW OF THE EARLY HISTORY OF THE SOCIETY

BY HERMAN L. FAIRCHILD

The remarkable success of our Society is primarily founded in the altruism of science—the unselfishness of the search for truth. This spirit found ex-

pression in the organization and administration and in the loyal support of its membership. An analysis of the immediate causes of our prosperity finds several factors which deserve attention.

Organization.—First in point of time, and fundamental, was the plan of organization, which was deliberately shaped by the founders and included several important and interesting features.

(1) The membership was limited to working geologists. This fact gave the Fellows an interest and pride in the Society, a feeling of ownership and control, an esprit de corps, which could never have been secured with a non-professional membership. This is probably the first geologic society limited to geologists.

(2) With a membership scattered over the continent and including three nationalities, a centralized administration was necessary. Large power was given to the Council and to the administrative officials.

(3) With this efficient concentration of power and responsibility was a truly democratic control by the membership, specially through the transmitted secret ballot. Every Fellow, anywhere, had the chance to make free choice at all elections. While the Council nominated the "regular" ticket for officers, the Fellows not only had the privilege of dissent, but, since 1893, any five Fellows could compel the official distribution of an independent ticket. The possession of this power avoided occasion for its use, and only once in the life of the Society has there been formal dissent from any nomination by the Council.

(4) The rules provided that the President and Vice-Presidents should not be eligible for reelection more than once until after an interval of three years. This compelled the honors to be passed around, while the executive officers, Secretary, Treasurer, and Editor, held without limitation, thus giving conservative administration. No President has held office two successive years, and only one a second term. In the 25 years we have had three secretaries, three treasurers, and two editors.

(5) Changing the Constitution was made difficult, requiring a three-fourths vote of the total membership. With a wise Constitution, this was a good safeguard, as it prevented changes that did not appeal to the membership. The few changes that have been made did not affect the general plan or purpose. In 1894 the words "North America," which limited the residence of Fellows, were dropped. At the same time the Treasurer was named with the other executive officers as eligible to reelection without limitation, the correction of what was probably an oversight in the original draft. In the absence of specific prohibition of such reelection of the Treasurer he had been previously continued in his office. In 1897 the Editor was made an elective officer and thereby a member of the Council (volume 9, page 400). In 1905 the requirement of a summer meeting was removed. A few changes have been made in the By-Laws, some of which will be noted later. (See the Bulletin, volume 15, page 597; volume 21, page 42.)

Bulletin.—Next to the efficient, democratic organization, the publication of the Bulletin has been the most important factor in the success of the Society. Outside its own Fellowship, the reputation of the Society is almost entirely based on its publication, which has carried the fame of the Society over the world. The form of the Bulletin is wholly due to W J McGee, and without its excellent dress the matter would have been less appreciated. The history of the Bulletin and the work of its editors needs to be reviewed.

The Constitution places the publications entirely in the control of the Council. At the organization meeting an "Advisory Committee on Publications" was named, with McGee as its Secretary (volume 1, pages 14, 15). With his characteristic enthusiasm and energy, McGee made, as preliminary to the report, a comprehensive study of scientific publications. The data of the comparative study were not presented to the Society, but the results as pertinent to the needs of the Society were embodied in a set of rules and a sample form of publication, which McGee presented at the second meeting of the Society, at Toronto, in August, 1889. This work was so thorough, refined, and every way commendable that the Council immediately made McGee Editor, and he was able to carry his plan into effect. He elaborated the "Rules Relating to Publication," and they were formally adopted by the Council April 21, 1891 (volume 5, pages 647-652; volume 21, pages 49-52).

The rules and the form and typography of the Bulletin have remained unchanged through these 25 years, which is the highest testimony to McGee's work. There has been some change in the style of paper, because of the impossibility of uniformity without extra cost, and some changes have been made in the form of distribution. Originally each article was bound and distributed as a separate brochure. About 1892 the Secretary, who has always had charge of the distribution and sale of the Bulletin, made a saving by having bound in brochure form only the number required for immediate brochure distribution, leaving the balance in sheets for collation as complete volumes. Since 1910 the matter has not been distributed even to the Fellows as separate brochures, but has been massed in quarterly issues, in order to secure second-class postal rates and for the sake of economy, about \$200 per annum being saved.

Dr. McGee edited three volumes of the Bulletin and then selected as his successor Joseph Stanley-Brown, who has done the laborious and not always agreeable or appreciated editorial work for 21 years, with small compensation. The Society owes him a great debt. The sustained high standard of the Bulletin as scientific literature and its uniform excellence as an example of fine book-making is due to his devoted work. He has held to typographical consistency in spite of criticism. His editorial inflexibility sometimes crosses an author's views on capitalization or punctuation, but we always yield to his knowledge of rhetorical technique.

The work of Editor is probably the least agreeable, and certainly the least appreciated, of all the duties of the officary. Here is a problem: Which is the more unsatisfactory task—that of the Treasurer in rounding up the delinquent Fellows every year or that of the Editor in reading hundreds of pages of perhaps illegible manuscript and making it conform to the style of the Bulletin, possibly against the author's views?

Many of the younger Fellows have never met the Editor, whose work as a financier in the Wall Street district has kept him from the meetings of the Society, and to some of whom he is an invisible and rather mythical editorial autocrat; but those who know him well wish continued strength to the editorial hand.

All the matter of the Bulletin may not rank in the highest class of geologic literature, but as a whole the Bulletin probably outranks all other geologic publications of its kind. We have to balance between the claims of Fellows

to the right or privilege of publication and the critical judgment of the Secretary and the censors. All papers are referred to critics, and refusal of publication is never based on the adverse opinion of a single censor.

In this connection, commendation should be given to the printers of the Bulletin. Judd & Detweiler, Washington, D. C., have been the printers from the first and have taken great interest and pride in the publication. Without their sympathetic cooperation it is not likely that the Editor would have been able to carry on his work.

The list of "Exchanges," or institutions, as free recipients of the Bulletin was compiled with much care, and the distribution of the first volumes was in 1891, to about 70 institutions scattered over the world. The aim was to place the Bulletin where it would be within reach and most useful to geologists, and with little or no reference to any return in kind. The number of exchanges has been kept small, so as not to cheapen the publication, varying at about 80, being at the present time 75.

Through the offices of the Editor and Secretary the Society has conducted a publishing business, and the Secretary has been running a sales-store by correspondence. The advertising and sale of the Bulletin to libraries and the public began in 1892. The price to libraries was made low, at a flat rate of \$5 per volume, recently increased to \$7.50.

The receipts from Bulletin sales has been an important item of income. The publication cost, not including distribution, of the first 16 volumes was \$30,629.55—an average, per volume, of \$1,914.35. The receipts from sale of those volumes up to the end of 1912 is \$10,836.17, being an average of \$677.25, which is practically one-third of the cost. This is a good showing for a technical publication.

Officers and Council.—Another important element in the immediate success of the Society was the tactful work of the organizing Secretary, Prof. J. J. Stevenson. On him fell the duty of devising methods of procedure, forms of printing, etc., to carry out the spirit and letter of the rules and the purpose of the Society. But the difficult task was the harmonizing of personal difficulties and jealousies that had arisen, due to the lack of a social gathering and coordinating, unifying body, and of gathering into the membership the leading geologists, necessary to give standing to the new Society. A Secretary without tact and personal influence could have killed the organization at the beginning, but Stevenson's subtle task was so well done that in two years he dared to trust the office in other hands.

The "team-work" of the Council and officers, with the confidence and cooperation of the Fellows, has been admirable. At bottom this is an expression of the unselfish, altruistic spirit which naturally belongs to the science; but there were favorable conditions. The six Councillors, with terms of three years, were ineligible for immediate reelection and represented different geographic sections of the continent. While the Council had large powers, there were effective checks. If we examine the Council minutes, which are open to our inspection, we will find no record of any serious disagreement or unpleasant episode. Matters were discussed always on the basis of the Society's good, and nearly always settled by unanimous consent. Frequent meetings in the first years kept the Council in close touch with and consequent interest in the work of the administrative officers.

As the Council nominated the regular ticket, which was always elected, selections were made with regard for efficiency. The ablest men are frequently not the best for cooperation and team-work on committee.

In the first years three names were submitted for each office, but it was pretty well understood that the first name of the three was the Council's real choice, and consequently the defeated two accepted their sacrifice. But the method was invidious, and in 1893 the rules were so changed that the Council could submit a single nomination for each office and not make unpleasant use of other names.

Another custom, since changed, was the practical selection of the President two years in advance, by first making him Second Vice-President and promoting. This plan had decided advantages. Everybody knew what to probably expect, and no one was hurt by being made Vice-President as a consolation. Moreover, it gave three continuous years in the Council, culminating as President, and until such culmination he was quite sure to attend meetings and take interest. Under the present plan, the ex-President is kept two years on the Council, but he has less personal incentive to hold him to the work.

The smooth running of the Society has been attributed by the writer to the *laissez faire* policy of the officers. We did not suggest changes unless they were so evidently desirable that they would be cordially accepted. The few changes in the Constitution were made with some difficulty, not from opposition, but because of the difficulty in securing a three-fourths vote from the widely scattered membership. The inertia of the Society kept it going and the officers had only to keep the machinery well oiled. The reports of the officers and Council were never even questioned, which is perhaps the best evidence of confidence in the administration. Up to 1896, during the years that the regular ticket carried only a single nomination for each office, there was never a single dissenting vote for the Treasurer and only one for the Secretary. We sometimes wondered if we were doing anything, since no one seemed disgruntled; or if our work was worth while, since no one seemed to desire the positions. The Editor could never have had such mental troubles, as he always had negative votes in plenty.

Membership.—Fortunately the Society came in time to have on its roll many of the great names in American geology—the men who were self-taught in the science, but who founded the schools. To many of the younger Fellows these men are only revered names, but to others of us they were admired and honored friends. Of those who have passed away, Hall and Alexander Winchell were at the organization meeting. Hall, Dana, Alexander Winchell, Dawson, Shaler, Le Conte, and Orton lived to become President. Newberry, Lesley, and Powell died before the Society could so honor them. Seven of the men who were at the meeting of organization are still with us—C. H. Hitchcock, Kemp, Stevenson, I. C. White, H. S. Williams, N. H. Winchell, and the writer.

The men who gave their adhesion to the Society by January 1, 1889, and known as "Original Fellows," numbered 112. In two years the Fellowship rose to 197, and increased to 237 in 1898. During those first ten years, which covered a time of financial depression, 37 Fellows were dropped from the roll for non-payment of dues, 10 resigned, and 21 died. The total number whose names had been on the roll during the first ten years was 305.

Our Constitution provides for Fellows, Correspondents, and Patrons. The writer is thankful that we have never been patronized, and personally he would choose to have no Correspondents. Efforts in the early years to select Correspondents failed, for two reasons—because of the difficulty in making a selection not invidious and because so many felt that as our membership had (after 1893) no geographic limitations, foreigners ought to become supporting Fellows of our democratic Society. In recent years 13 men have been elected Correspondents.

Meetings.—The program and manner of the early meetings were quite like those of the present time—rather informal, yet always with sufficient dignity; never frivolous and invariably courteous. The writer recalls no instance in the long series of meetings of discourteous conduct or undiplomatic language. Yet men who were soft-spoken in the meetings of the Society might be different in the meetings of Section E. Every one seemed to recognize the "Fellowship." At the end of the first decade it was well said that "the Society has united the geologists of the continent, produced harmony of feeling, thought, and labor, created and cemented friendships, and prevented the geology of America from becoming provincial."

It is likely that a somewhat freer and more frank criticism of papers would now be more profitable.

As the Society was an outgrowth of Section E, American Association for the Advancement of Science, the Constitution provided that a summer meeting should be held in conjunction with the Association. As years passed the summer meetings became small and rather perfunctory, as the Fellows were mostly afield; but such meetings were held until the Association changed its regular time of meeting from summer to winter. The last summer meeting, the fourteenth, was held at Pittsburgh in 1902. The clause of the Constitution requiring summer meetings was dropped in 1905.

Sections.—The Fellows residing in the western part of the continent and unable to regularly attend the meetings were, in 1899, authorized to organize as the Cordilleran Section. Quoting from the proceedings of the meeting which voted such authority: "No one spoke in opposition, but some Fellows expressed doubt and anxiety as to the effect of the movement" (volume 11, page 588). There was fear that other geographic sections of the continent might desire similar autonomy and the Society disintegrate. Recently another Section has been organized, not as geographic division, but as scientific specialization—the Paleontologists.

The proper pronunciation of Cordilleran was questioned and the point referred to the Council. The report was made three years later and it was recommended that the name be given the Spanish sound—Cor-dil-ye-ran. The writer does not recall the reason for such unusual delay by the Council.

Finances.—The funds of the Society have been derived entirely from the fees and dues of the Fellows, sales of the Bulletin, and interest on deposits and investments. The Society has never solicited nor received any gifts and has been entirely independent of outside help of any kind. Up to this time the absence of an "endowment" has been an advantage. It is better to have saved by economic administration the large permanent fund now in the treasury than to have received it as a gift.

Prof. H. S. Williams was the Treasurer for the first three years. From

1892 to 1907 Dr. I. C. White collected the membership dues and conserved the funds without other recompense than the pleasure of service, and at some personal cost. During his term the permanent fund, consisting mainly of life commutations, increased from \$1,000 to \$10,000, in spite of the large expense of the Bulletin and of a scattered membership.³

Library.—The printed matter sent us by the Exchanges accumulated rapidly and its disposition became a problem. One suggestion was that we give it away or distribute it in some manner. That would not have been courteous to the donors. It was decided to retain it for a library, and after investigation and negotiation the Case Library of Cleveland, Ohio, accepted it on deposit under conditions very favorable to the Society. The conditions of the contract will be found in the Bulletin, volume 6, pages 427-428. The Secretary was Acting Librarian until 1897, when the Council recommended that the office of Librarian be created, and Prof. H. P. Cushing was elected to the office, which he held to this year. The accessions to the library were published in the Bulletin from volume 6, 1894, to volume 20, 1909, when the material was sold to the Case Library. At the date of sale the number of volumes, aside from unbound pamphlets and maps, was over 2,000.

Annual Dinner.—The annual dinner, which has become an established social feature, had its beginning in 1891, at Columbus, Ohio. We were all housed in one hotel, on American plan, and arranged for dinner together in ordinary. Twenty-three Fellows were present and three visitors. Professor Emerson was the toastmaster, and this was the occasion when he was discovered to be the prince of toastmasters. It was a very informal affair, and because of its lack of formality no one felt any embarrassment on being called, and nearly every one spoke.

Name of the Society.—The younger Fellows may not know, and the older may have forgotten, that the original name of the Society, in the Provisional Constitution, was the American Geological Society. If not so dignified, it was a shorter name, and is now frequently used by the public in referring to us. The change was made at the first meeting (see volume 1, pages 5, 13). We quote from the minutes of that meeting: "It was also formally agreed that Fellowship in the Society should be indicated by the initials 'F. G. S. A.,' and it was recommended that this title be employed on all suitable occasions." The recommendation has not been obeyed. How many Fellows have found the "suitable occasion" when they wished or dared to append these initials to their names? Or would the initials "F. A. G. S." have been more usable?

Collection of Photographs.—This is a fine and interesting property of the Society of which little notice has been taken in recent years.

The suggestion of such collection was made in 1889 by H. S. Williams and was brought to the attention of the Council by J. F. Kemp. A committee, with Kemp as chairman, was appointed by the Council in April, 1890. The report of that committee, made by J. S. Diller in December, 1890, will be found, with a list of 290 photographs, in volume 2 of the Bulletin, pages 615-630. Annual reports, with lists of accessions, were published in the Bulletin up to 1901, when N. H. Darton, who had succeeded George P. Merrill as chairman, published a brochure of nearly 100 pages, giving a classified list of 1,418

³ The figures in detail will be found in the Bulletin; for the first ten years, vol. 10, pp. 416-420; for the period of Doctor White's service, vol. 18, pp. 564-567.

photographs (volume 14, pages 377-474). The collection is still at the United States Geological Survey and in the custody of Mr. Darton.

Migration.—Doubtless there would be some advantage in a permanent headquarters or “home” for the Society; but whatever may have been the loss, there has certainly been a decided gain by the migratory meetings in interest and support and probably in attendance. The Society has escaped undue influence or control of any place or group of men. In visiting different sections of America and many centers of geologic interest and activity, the Society has gone to the Fellows and the better fulfilled its object—“the promotion of the Science of Geology in North America.”

HISTORY OF THE BULLETIN

BY J. STANLEY-BROWN

Mr. President and Fellow Members of the Society:

It is more than a *pleasure* to have been remembered on such an occasion as this; it is an *honor* to be asked to appear in company with two such revered associates—associates to whom we all gladly and publicly acknowledge our indebtedness for the substantial aid they have rendered in the construction of the sound and enduring foundation on which the Society rests today.

Frankly, the Editor finds no logical reason why *he* should have received such recognition, except on the theory that, by virtue of his office, it was unavoidable.

You will recall that there have been but two editors. The reason for this is that one would not stay and the other would not quit. While the present incumbent has not grown gray—at least not very gray—in office, he certainly has attained his editorial majority, and the length of his official life is unequaled by that of any other member of the Society. To forestall the critics, he hastens to add that he does not confuse *quantity* of service with *quality*, and wishes it clearly understood that there are no thanks due him; quite the reverse, and he desires to avail of this occasion to express his appreciation of the opportunity, so long and so courteously extended to him, of contributing even a little to the cause of geology.

That the Society's form of publication is one of which members may justly be proud will be admitted by all who read its “Proceedings.” Its excellence was not due to mere chance, nor the result of growth; it was started right in its inception, through the agency of a very high order of gray matter, and in this connection permit me also to pay a richly deserved tribute to the memory of the originator of the “Bulletin”—*W J McGee*.

As Minerva sprang, full grown and completely armored, from the brain of Jupiter, so was the Society's publication created—a model of form and efficiency—by the sole effort and peculiar genius of one of the most competent and brilliant scientific minds the West has produced. In its essential features the Bulletin stands today as it did at the time of its creation.

Of course, the greatest contributory cause of the Bulletin's success is the character of the subject-matter offered by the members. While this, in the main, has been all that could be desired, the wise but somewhat severe method provided for reviewing papers before their publication has been accepted invariably in a fine spirit by contributors, thus aiding greatly in maintaining

the high standard originally adopted and steadfastly insisted upon by the Council. It is not exaggeration to assert that the annual volume is welcomed by those interested in this branch of science as a valuable and substantial contribution to the geological knowledge and literature of the world. If minor criticism is allowable on such an occasion, the Editor could make an earnest plea for greater condensation.

You have already been told how the way to its success was paved by those great creative leaders who blazed the geological trails in our country. With the vision of the prophets of old, they saw that ultimately the United States was to be the great luminary in the geological firmament. They realized the necessity for some medium of expression free from all trammel—a medium which would encourage and unify by publication, as well as by association, the army of younger workers who would be required in the field of American geology.

Their method of procedure and its results were alike admirable. As the aged negro, who, when overtaken by a violent storm, accompanied by great darkness and terrific thunder, prayed for more light and less noise, so the founders of our Society sought and obtained the maximum distribution of geologic light with the minimum of administrative noise.

Although formed on lines of severe simplicity and having to do almost entirely with those of modest means, the organization has given to the scientific world more than 15,000 pages of text, illustrated with 1,122 plates and many more text figures. It has expended for that purpose at least \$50,000, exclusive of the cost of administration, and has at the present time substantial assets in its treasury. This is financial thrift and skill of a sufficiently high order to warrant representation in the management of the Government's new monetary scheme.

The Society's name and its publications are known wherever geology is studied or taught, and this achievement has been greatly aided by the unswerving loyalty and devotion which characterize the membership. No member is ever so busy as to be unwilling to take time for the Society's affairs.

Another great tower of strength has been the conservatism exhibited in the matter of administrative changes. Of course, annual presidential rotation was a necessity, conferring, as it does, great distinction, but in twenty-four years there have been but three secretaries, three treasurers, two librarians, two editors, and one printer, who, it should be stated, takes as much personal pride in the Bulletin as if he were an actual member. Here, again, is manifested the benefits arising from the spirit of cooperation.

Surely on such an occasion as this indulgence in a little personal reminiscence is permissible. In the past twenty-one years the office of the present editor has been most peripatetic; in fact, frequently it has been in his satchel en route to distant places. The Bulletin has been edited from beautiful Washington to the wilds of Alaska; from gay Paris to the quiet of Long Island; on railroad trains and on steamship lines; in the field, and even while studying the financial geology of the Wall Street quadrangle. Permit me to digress a moment in order to demonstrate the fact, as yet quite unknown, that this last named district presents many geological facies of profound interest. In this area subterranean, dynamic forces of great power and magnitude are continually at work. Financial geology is made fresh every minute—sometimes

while you wait. Within that labyrinth of canyons, still in the making, there are many strata resting conformably and unconformably one on the other. In tracing the various formations, you find that the Morganstein grades so insensibly into the Morgansheim, that it can not readily be determined where one begins and the other ends. Flora is wholly lacking, but a rich and peculiarly recent fauna is found, though well preserved fossils are extremely rare. This is due to the rapid shifting of formations and the resulting metamorphism which is continually going on. It is in the domain of economic geology, however, that the Wall Street quadrangle is especially impressive. Some of the strata are auriferous, while others are not. Many possess vast stores of the precious and other metals, and even diamonds are known to occur. These riches frequently are well nigh inaccessible, and to secure them it is necessary to resort often to more subtle and searching methods than those furnished by dynamite or the cyanide process. Thus you see that just as the Geological Society was in a position to furnish the talent necessary to unravel the mysterious volcanic manifestations at Panama, so now it is equipped to solve those intricate and complex problems to which the experts of the Interstate Commerce Commission, the Pujo Investigating Committee, and the leaders of the three political parties can find no open sesame. The versatility of our beloved Society is indeed amazing.

Your Editor fully sympathizes with Robert Louis Stevenson's expressed belief, that "he who loves the labor of his work is called of the gods." Neither time, place, nor circumstance have been permitted to interfere with editorial duties, and no engagements have been so compelling that there has not been always a little time available for the next manuscript. In his efforts in their behalf, the Editor has had always the cordial support of the contributing members, and while on a few rare occasions an author may have seemed a little "het up," it was recognized that it was merely temperamental. Actual friction has been avoided invariably by adhering strictly to the policy of not writing letters, as well as by remembering that the chief function of an editor is not to be seen or heard, but to be felt. In this connection permit me to urge my successors not to take their job too seriously, and never, for their own peace of mind, to lose their sense of humor. It will not be their function to run the Society. They must remember that authors often work under pressure and many disadvantages. The contributors are usually jolly good fellows who mean to be fair and considerate. Just lend them a helping hand in every way you reasonably can and your editorial journey will be along a pathway strewn with flowers, as has been that of the present incumbent.

In celebrating the quarter century of its existence, the Society wisely maintains its customary simplicity. Only on its social side has it been affected by the trend of hectic, modern life. The time was when the Society was wont, after the serious work of the meeting was over, to repair to a "rathskeller," or some equally humble hostelry, and, after suitable refreshment, to listen delightedly to the efforts of the patrons of the "School of Oratory" early established by the Society for the benefit of its budding young geologists. In time this entertainment, charming as it was, palled a little, and it was felt by the giddier members that the Society should be somewhat more modish, and so the "movies" and "polite vaudeville" *crept in*, while, owing to changing economic conditions, the price per plate *crept up* from one dollar to two fifty.

Those of us who believe in social progress and woman's rights may yet be gratified by seeing the introduction, on festal occasions, of the tango and the turkey trot, and possibly the cabaret—that wonderful modern institution which has taken the “rest” out of restaurant and put the “din” in dinner.

But, returning to seriousness, let me use this last minute of my allotted ten to say that in all its moods and tenses the Society has ever cultivated the spirit of good fellowship—the keystone of the structure. Let that habit not only continue, but be strengthened as the years go by. Let us be as broad as the universe we study and as patient as the geologic time we seek to measure. Let us welcome within our gates every one interested in any form of geologic research, and the next anniversary day will mark the close of another period more brilliant, more useful, and more gratifying even, than the one we now celebrate.

The following paper by N. H. Winchell was given at the annual dinner of the Society on December 31, but is inserted here for record, as being a part of the quarter-centennial celebration:

REVIEW OF THE FORMATION OF GEOLOGICAL SOCIETIES IN THE UNITED STATES

There was an “American Geological Society” in 1832 at New Haven, Connecticut, but it faded out in the glare of the chemical and physical sciences which bloomed brilliantly at that time in New Haven. I have not been able to get any detailed information concerning it. President Smith's address at this meeting referred at some length to this early organization.

About the same time was organized the Geological Society of Pennsylvania, 1832. At a meeting of February 22, 1832, the officers were John R. Gibson, President; Nicholas Bibble, Vice-President; Stephen S. Long, Vice-President; Henry S. Tamer, Treasurer; Peter A. Browne, Corresponding Secretary; George Fox, Recording Secretary.

This society sent out a circular signed by John Gibson and George Fox, announcing the organization and asking assistance in getting information and specimens. The organ of publication was Featherstonhaugh's *Monthly American Journal of Geology*.

This Society seems to have aimed to develop the geology of Pennsylvania specially, but its plan of operation covered other States. It came quickly into competition with the Philadelphia Academy of Science. Its transactions were published in Featherstonhaugh's *Journal* at first, but as that journal passed through only one volume, it is unknown to me whether the Society survived long after the death of the journal. It appears that there was close sympathy between them, and it may be presumed that Mr. Featherstonhaugh was the instigator and prime mover of both.

There may have been other local geological societies in the country since 1832 whose records have not been published, but I have not heard of any.

The period of discussion and gestation prior to the birth of the present Geological Society of America extended from August, 1881, to August, 1888—seven years.

A few weeks before the 1881 meeting of the American Association for the Advancement of Science, at Cincinnati, Professor Chamberlin called on the

speaker at his home in Minneapolis. The Western Society of Naturalists had been organized several years earlier, and one of its annual meetings was announced to take place at some point in the Mississippi Valley. In the conversation which took place in my parlor the suggestion was made by the speaker that the geologists of the western part of the country ought to be organized into a Mississippi Valley Geological Society. Professor Chamberlin immediately fell in with the idea, and it was agreed by us that the project should be broached at the approaching meeting of the American Association for the Advancement of Science at Cincinnati. But this idea expanded, in conversation with geologists at that meeting, into greater dimensions, and it was resolved to organize the geologists of America in a general society.

The first informal meeting embraced those present at Cincinnati and was held in the room of Section B, at 5 p. m., August 18, 1881. A committee was chosen to draft a constitution, consisting of George C. Swallow, of Missouri; N. H. Winchell, of Minnesota; S. A. Miller, of Ohio; William J. Davis, of Kentucky; John Collett, of Indiana, and H. S. Williams, of New York.

On meeting, the committee elected Winchell chairman and Williams secretary, and Miller was designated to draft a constitution for the proposed society. This constitution was presented the next day at an adjourned meeting of the committee, but after considerable discussion it was finally decided that it was best to defer more definite action to the next meeting of the American Association, and that meantime the committee prepare and distribute widely a circular asking for the opinions of geologists generally, the replies to be reported at the next meeting of the Association, which was to be held at Montreal. Before the issuing of this circular, John R. Proctor, State Geologist of Kentucky, was added to the committee. This circular was drawn up by the chairman of the committee and, on submission to the members of the committee, was approved unanimously by them. It was based almost entirely on a previous rough draft prepared by Williams and presented to the committee by him at one of the preliminary meetings at Cincinnati. Its main points are as follows:

The committee are desirous of eliciting opinions from all active and professional geologists, to the end that more judicious and effective action may be taken at the next meeting.

1. The science of geology, with its kindred branches of paleontology and lithology, has made rapid progress in America—perhaps more rapid than in any other country—in the last 20 years.

2. The literature of geology is largely distributed through numerous scientific journals and in the proceedings of miscellaneous scientific societies, to procure which is difficult and expensive.

3. The present facilities afforded through the American Association for the Advancement of Science are insufficient and unavailable by the working geologists of the country—because: (a) The meetings are held in the summer, which is the geologist's working season. In order to be present, he must interrupt his work and leave the field, often at considerable expense, especially if he has a party with him. (b) Its brief meetings partake largely of the nature of vacation pleasure parties, and much of the time is engrossed by reception, gratulation, and excursions. (c) There is no sufficient avenue of publication of the work of geologists. (d) The Association has become so large, widespread, and popular in its work, membership, and organization

that its spirit, necessarily and properly, is not favorable to the development of any special work through its own agency.

4. The geologists, as a body, have no way of expressing their views on important State, national, or international measures, except through the medium of the American Association, at the meetings of which there is a perceptible and increasing lack of attendance and interest on the part of geologists, in consequence of which the actual views of the geologists of the country on such questions can not be obtained and expressed correctly.

5. There is no strictly geological magazine or journal in America.

6. There is no strictly geological society in America.

7. There are numerous such societies and journals in Europe, as well as journals and societies devoted exclusively to the branches of paleontology and mineralogy.

The committee desire also to disclaim any intention to trespass on the field and plans of the American Association for the Advancement of Science or to criticise it in any way as to the discharge of its functions. Its tendency is to popularize science and to advance its acceptance by the world by diffusing scientific knowledge and by announcing important discoveries, and, as such, its sphere of activity is one that no special scientific body can occupy, but which still will be aided by the existence of tributary organizations, such as that contemplated by this circular.

At Montreal responses were read from the following geologists: S. A. Miller, James Macfarlane, Franklin Platt, W. P. Blake, J. D. Dana, P. A. Chadbourne, J. E. Todd, E. W. Claypole, Wm. M. Davis, M. C. Read, Chas. E. Billin, W. H. Pettee, Geo. H. Stone, John Collett, R. E. Call, Warren Upham, W. G. Platt, C. A. Ashburner, R. T. Cross, G. K. Warren, A. Winchell, Robert Bell, P. W. Schaeffer, S. E. Tillman, E. O. Ulrich, C. H. Hitchcock, Edward Orton, W. J. Davis, J. W. Dawson.

The official report of the proceedings at Montreal states that A. Winchell was chosen chairman and C. H. Hitchcock secretary. Several sessions were held. Ninety answers to the circular which had been issued were reported by the chairman of the committee, all but two of which spoke favorably of the project. The secretary (Williams) reported answers from 30 persons and S. A. Miller reported answers from six persons, all favorable, making a total of 126 opinions in favor of and only two dissenting from the formation of the proposed society.

A committee consisting of Jed Hotchkiss, R. P. Whitfield, and C. H. Hitchcock, appointed to consider the situation, recommended that the first step to be taken should be the establishment of a geological magazine. This report was accepted and adopted. The Cincinnati committee also reported a proposed constitution, which was discussed and laid upon the table pending further labors by the committee and a report at the Minneapolis meeting in 1883.

At the Minneapolis meeting of the American Association for the Advancement of Science (1883) those who had been active for the proposed geological society met August 21 and listened to further discussions and some objections. Some dilatory motions were brought forward and carried, namely, that a committee be appointed to confer with the Mineralogical and Geological Section of the Philadelphia Academy of Sciences with reference to the formation of an American society and the establishment of a geological magazine. Prior

to this a committee had been appointed with instructions to confer with Major J. W. Powell to ascertain what encouragement could be afforded by him in the support of a geological magazine. These special committees, however, accomplished nothing, except to delay the project and to discourage those who were in favor of the proposed society; and the friends of the new movement became very much disheartened by the expression of unfavorable views at Minneapolis. These adverse opinions were stated by several of the oldest and most prominent geologists, and they served to dampen the ambition of those who, though younger, had been zealously promoting the proposition.

Four years later various causes led some of these opponents to change their minds and to solicit a continuation of the plan that had been proposed, and in particular the speaker recalls such correspondence with Dr. J. S. Newberry.

The chairman and the secretary of the moribund organization, Winchell and Hitchcock, convinced that nothing would be done by other parties, under implied instructions and responsibility from the meeting at Minneapolis, by virtue of their office sent out a call to meet at Cleveland, Ohio, in connection with the American Association for the Advancement of Science, 1888. The call, as issued, provided that the new society should be composed only of members of Section E of the American Association. This was in consequence of fear, expressed by some of the older geologists, that such an organization would clash seriously with the Association; and their love for the Association, with which they had been connected actively for many years, was greater than for any new geological organization, which appeared to them like a phantom which would be likely to have only an ephemeral existence.

Meanwhile several geologists, depending largely on the action of the Montreal meeting and on the frequently stated advice of individual geologists, unwilling to delay longer the issuance of a geological magazine, boldly took the initiative and established the American Geologist, the first number appearing January, 1888. The call for the Cleveland meeting appeared in the "Geologist" for June, 1888.

It is enough to say, further, that this call met a cordial reception and that at Cleveland very much renewed interest was evident. Committees were appointed to prepare a constitution, and this constitution was adopted at a meeting held at Ithaca, New York, in December, 1888, the present meeting being the 25th anniversary of its adoption.

The Society proceeded, at the conclusion of Mr. Stanley-Brown's address, to the consideration of scientific papers.

TITLES AND ABSTRACTS OF PAPERS PRESENTED IN GENERAL SESSION AND DISCUSSIONS THEREON

MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

BY W. H. HOBBS

(Abstract)

The structure of arcuate mountains was discussed both in respect to the plan of arrangement and the vertical cross-sections, the Alps being taken as a

type. Contrary to the rather generally accepted view, it was argued that the distribution of the active tangential thrusts during the formation of the arc is centripetal and not centrifugal with respect to the center of the arc. This requires that in the formation of anticlines the active thrust which produces them comes from below and in front and not from above and behind the rising arch. For this reason folds in later stages become *underturned* and *underthrust*, but are never "overturned" or "overthrust." True, overturning and overthrusting take place, however, in the snouts of glaciers, where overturned and overthrust folds are produced, though with different characters dependent on this manner of formation.

A study has been made of the actual loads and of the percentage of total loads which a competent stratum may lift from underlying formations while rising to form an arch, and deductions have been drawn concerning the effect on the form of the fold, etcetera. The special conditions which determine failure (sliding) within an arch of strata, and in later stages the complex *Deckenbau* of the Alps with its drag-folds and, listric surfaces at the forward end, also received consideration.

Read in full from manuscript.

EARLY TERTIARY GLACIATION IN THE SAN JUAN REGION OF COLORADO

BY WALLACE WALTER ATWOOD

(Abstract)

In conducting an areal survey of the northwestern quarter of the Montrose Quadrangle, which is located near the northwestern base of the San Juan Mountains, a number of exposures were discovered in which there are glacial deposits overlain by conglomerates and volcanic rocks of known Tertiary age. These glacial deposits are divisible into two distinct sheets of till. The ice was presumably in the form of Alpine glaciers.

Presented in full without notes.

DISCUSSION

Dr. I. C. WHITE: Mr. Atwood might have added Brazil to the list of countries where Permian glaciation had been discovered. The first definite and positive announcement of Brazilian glaciation was made in 1906 by myself and the evidence therefor published in my final report of the Brazilian Coal Commission, issued in 1908. Doctor Derby had previously intimated that Permian glaciation in Brazil was possible, but had made no positive statement on the subject. Doctor Woodworth, of Harvard University, confirmed my conclusions by finding striated boulders in the Permian tillite of Brazil in 1910.

Dr. R. D. SALISBURY: In connection with the closing Paleozoic glaciation, it is now known that glacial beds of Permo-Carboniferous age occur in the Sierra Ventane Hills of Argentina. This discovery was made by Doctor Keidel.

Professor SALISBURY asked Professor Coleman whether it was now possible to state the age of the Canadian glacial beds more accurately than heretofore.

Professor COLEMAN replied that the beds were at the base of the Lower

Huronian, and went on to say that the Lower Huronian tillite of Ontario occurred at various points over an area of 20,000 square miles, and that the materials from it had been accepted as glacial by most of the best glacial geologists of the world.

DR. WHITMAN CROSS: I have had opportunity to examine, in company with Professor Atwood, the locality near Ridgway where the till beds occur below the Telluride conglomerate and the San Juan tuff. This stratigraphic position seems beyond question. The Eocene age of the tills is indicated by what is known of the Tertiary history of the San Juan region, as set forth in the Ouray and other folios of the Geological Survey. The volcanic eruptions of the San Juan region began at or near the close of the Cretaceous, as shown by the Animas beds near Durango of andesitic debris and containing dinosaur and plant remains correlating them with the Denver beds. A flora has been found in certain tuff beds of the Potosi volcanic series, in the central San Juan, which has strong affinities with the flora of Florissant, Colorado, according to Doctor Knowlton. This indicates an Oligocene or Miocene age for those tuffs. The known record of long periods of volcanic eruption and erosion between the deposition of the Miocene tuffs and the Telluride conglomerate make it almost certain that the latter is of Eocene age. The till found by Professor Atwood is presumably not much older than the conglomerate.

Further remarks were made by Messrs. A. H. Purdue and Charles Schuchert.

ORIGIN OF PILLOW LAVAS

BY J. VOLNEY LEWIS

(Abstract)

The peculiar structure known as pillow lava (otherwise described as globular, spheroidal, ovoid, ellipsoidal, lenticular, and concretionary) has been observed, chiefly in the last 20 years, at several localities in America. Numerous examples are also known in the British Isles and on the continent of Europe. The origin of the structure has been attributed to a great variety of causes, including spheroidal weathering, spheroidal jointing, columnar jointing, with subsequent movement of the columns on each other, concretionary action, explosive eruption (bombs in agglomerate), normal flow of lava on land, viscous flow and fracturing of stiff lava, flow of lava under water, and intrusion into unconsolidated sediments.

At all of the various localities that have been described the structure is essentially the same as at several places in the later Newark basalt flows of north central New Jersey, only one of which has been briefly described under the name of pahoe-hoe. On the basis of its relation to the associated sediments and of minor differences in the development of the structure itself, its origin is here interpreted as a normal flow phenomenon, either subaerial or subaqueous, when a highly fluid lava is rapidly chilled at the surface. In New Jersey it seems to be wholly subaerial.

Presented in abstract without notes.

DISCUSSION

Prof. WILLIAM H. HOBBS: A recent visit to the locality at Aci Reale, in Sicily, where pillow lava is exposed, enables me to say that the pillow structures are strikingly like those shown in some of Professor Lewis's pictures. The late Dr. Tempest Anderson has described watching the formation of pillow lava where the lava stream from the eruption of Matacanu in 1906 was discharged into the sea. There is, I believe, a general acceptance of the view that the ellipsoidal basic rocks of the Lake Superior province were extruded into water.

Prof. J. P. IDDIGS: W. L. Green has described the flow of lava from the eruption of 1859 on Hawaii over a low shelf into the sea. It came from under the crust in flattened spheroidal masses which fell into the water and must have produced an aggregation with the structure of so-called "pillow" lava.

Prof. A. P. COLEMAN suggested that pillow structure was really due to rapid cooling, perhaps not necessarily under water.

The Society adjourned about 12.45 o'clock, and reconvened in three sections at 2.30 o'clock.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE FIRST SECTION
AND DISCUSSIONS THEREON

The first section met, with Vice-President R. D. Salisbury as presiding officer and E. O. Hovey as Secretary, and took up the papers entered in the printed program under Group A: Dynamic, Structural, Glacial, Physiographic.

EARTHQUAKE SEA WAVES

BY HARRY FIELDING REID

(Abstract)

The explanations so far offered of the origin of great waves set up by submarine earthquakes are unsatisfactory, among other reasons, because they do not explain why the waves first appear as a depression of the water at some ports and as an elevation at others. The elastic rebound theory offers a satisfactory explanation of these facts. The accounts of some great submarine earthquakes and the records of tide gauges were examined and shown to support the theory.

Presented in abstract without notes.

DISCUSSION

Prof. WILLIAM H. HOBBS: It is not clear to me in what respect Professor Reid's theory of tsunamis accords better with the facts of observation than that which assumes the sinking of a section of the ocean floor with occasional uplift of a neighboring block on either side. Although the arrival of a positive wave in advance of a negative at some shore stations appears to have

been established, yet the observations indicate that the negative wave is generally the precursor of the destructive positive wave. On the western coast of South America, where there is a long record of tsunamis, the people are accustomed to rush inland when the sea withdraws suddenly.

Prof. D. W. JOHNSON asked whether the facts advanced by Professor Reid might possibly be explained by the fact that positive waves travel more rapidly than negative waves in the same depth of water. Thus an earthquake may give rise to a negative wave which is followed by a positive wave of greater velocity. On some coasts the negative wave arrives first, on others the positive. If waves of one phase overtake or are overtaken by waves of the opposite phase, the smaller wave is extinguished and the surplus of the larger wave propagated independently, as shown by G. Scott Russell. This might further explain the lack of uniformity in the direction of water movement at different ports.

Brief reply was made by Professor Reid.

*RECENT EARTHQUAKES IN PANAMA AND THEIR CAUSES*⁴

BY DONALD F. MAC DONALD⁵

Presented by title in the absence of the author.

*CRITICISM OF THE HAYFORDIAN CONCEPTION OF ISOSTASY REGARDED
FROM THE STANDPOINT OF GEOLOGY*

BY W. H. HOBBS

(Abstract)

An attempt to show that the facts from which Hayford's deductions have been drawn are open to an alternative interpretation more in harmony with the facts of geology.

Read in full from manuscript.

*EARTH-MOVEMENTS IN THE MINNESOTA PORTION OF THE LAKE AGASSIZ
BASIN DURING AND SINCE THE LAKE OCCUPANCY*

BY FRANK LEVERETT

(Abstract)

As a result of somewhat detailed investigation of each of the successive shorelines of Lake Agassiz, the present season data sufficient for determining the progress of the northward differential uplift during the life of Lake Agassiz have been obtained. These results extend along the highest shore beyond the limits of work by Warren Upham, presented in his monograph on

⁴ The papers which were passed over at the first call and not read at a later session have been entered "by title" in their original position in the program.

⁵ Introduced by E. O. Hovey.

Lake Agassiz, and cover also, with similar fullness, the lower shorelines, whose tracing was not attempted by Upham.

Presented in full without notes.

DISCUSSION

Dr. R. D. SALISBURY: I should like to ask Mr. Leverett how accurately the water level of an extinct lake can be determined at any given point? May not the level taken be a beach several feet above the lake or a bar several feet below? If so, would this not account for apparent local irregularities in rise?

Prof. A. P. COLEMAN: One can not expect to find a rise corresponding to the relief of load from the removal of every lobe of the ice. One would expect the earth's crust to respond only in a general way to the relief of load, and we actually find elevation only where ice once existed.

Further remarks were made by Dr. J. W. Spencer, and Mr. Leverett replied.

TIME MEASURES IN THE NIAGARA GORGE AND THEIR APPLICATION TO GREAT LAKE HISTORY

BY FRANK B. TAYLOR

(Abstract)

The time estimates for the five sections of the Niagara gorge are as follows, the first or oldest being placed at the bottom:

Fifth section: Upper great gorge.....	3,000 to 3,500 years
Fourth section: Gorge of the Whirlpool Rapids.....	5,000 to 8,000 "
Third section: Lower great gorge.....	2,500 to 3,000 "
Second section: Old narrow gorge.....	8,000 to 13,000 "
First section: Lewiston Branch gorge.....	1,500 to 3,000 "

These estimates are, as here shown, merely approximations between fairly wide limits. The time for the making of the whole gorge is believed to lie somewhere between the totals of the two columns; or, in round numbers, between 20,000 and 30,000 years. The uncertainties of the time estimates for the two narrow sections—the second and the fourth—both of which were made with only 15 per cent of Niagara's present volume, introduces a possible necessity of extending the time a few thousands of years, but probably not more than 5,000 years at the greatest. This possible necessity is regarded as remote rather than probable.

On the basis of these time estimates for the different sections of the gorge the correlative stages of the Great Lake history were reviewed, the main object of the paper being to describe the conditions of the lakes during the making of each gorge section and to point out the principal features then made, the time taken for the making of these features, and the time during which they have since been exposed to weathering and erosion.

The distribution in time of the uplifts which have affected the Great Lakes

region was also briefly considered. In the concluding part of the paper some remarks were made on the bearing of the Niagara time estimates on the duration of the Wisconsin Glacial epoch and on the date of its maximum.

Presented in full without notes.

DISCUSSION

Dr. J. W. SPENCER: My friend, Mr. Taylor, has given a good account of the glacial and beach phenomena, but he adopts as the coefficient of recession of Niagara Falls the exaggerated rate of the concentrated flow, 750 feet wide, as that of the mean rate, making the gorge 1,200 feet wide. He discredits James Hall's survey of the American Falls on the strength of pictures by Basil Hall (1897), which, in comparison with Gilbert's pictures (1895), would indicate an advance of the falls in place of retreat, if B. Hall's pictures were correct. Mr. Taylor makes the width of the Whirlpool Saint David's gorge increase to some 4,000 feet, although the rocks found prove it to be only about 2,000 feet. He also says my borings were stopped (269 feet) by boulders, although my printed statement says quicksand. He discredits wood and deoxidized soil as evidence of an interglacial epoch. Using his figures, the interglacial epoch recognized by him could have lasted only from 1,200 to 2,400 years, and the end of the Ice Age dated 4,500 years ago. While using my other soundings, Mr. Taylor denies the validity of those under the falls, although otherwise confirmed. Mr. Taylor also denies the value of the borings at the Whirlpool Rapids showing their character. He ignores the intermittent lowering of the later level, although he knows of the Roy Terrace.

Applying the differential height and volume of the falls (according to Mr. Taylor's history of the gorge) to the work performed, the results establish a new arithmetic.

$$3 \times 1 = 10, 3 \times 1 = 12, 5 \times 1 = 1, 15 \times 1 = 5.$$

Newton and Leibnitz independently invented the differential calculus, but this new form of mathematics surpasses their great work. Having recalculated the differential work of the falls, I find the figures varying so little from 39,000 years that even my allowance of 4,000 years either way is not reduced in the figures.

Prof. A. P. COLEMAN: An estimate of the age of Lake Ontario, made from the recession of Scarboro Heights, gives from 8,000 to 9,000 years. Probably the whole length of time since Niagara began was three times as long—that is, 24,000 to 27,000 years. This corroborates Mr. Taylor's results.

Prof. H. F. REID: The glaciers, as we now know them, are apt to advance more rapidly than they retreat, and the rate of retreat is apt to increase as the retreat progresses. Perhaps this should be taken into consideration in estimating the time between certain positions of the ice end.

Mr. Taylor replied, defending his estimates of time.

ILLUSTRATIONS OF INTRAFORMATIONAL CORRUGATION

BY JOHN M. CLARKE

(Abstract)

An effective view of an exposure in the Grande Grève limestones, referred to by Logan and very difficult of access; also some suggestions in regard to the corrugated Hillsborough (New Brunswick) gypsums, supplemented by an illustration deposited nearly a century ago in the Albany Institute.

Presented in full without notes.

DISCUSSION

Mr. F. BERCKHEMER gave examples of probable "subsolvifluction" from the Upper Devonian at Mill Rifts, Delaware River, Pennsylvania; the Beekmantown of East Creek, New York; the Quaternary clays at Catskill, New York, and the Upper Malm of Mergelstetten, Württemberg.

Dr. HENRY M. AMI: In the Province of Quebec, Canada, similar corrugations occur in the brown-colored shales of Upper Ordovician (Lorraine) age, on the north side of the Island of Orleans. The corrugated layer, in some instances, is only 5 inches in thickness, over which and under which are perfectly horizontal and undisturbed strata. At Hillsborough, in New Brunswick, the gypsiferous deposits present evenly banded structure, between which there occur neatly folded layers in the form of ribbon-like corrugations. These folds, when seen on the divisional planes of stratification, have the appearance of ripple-marks, but are probably quite distinct.

Dr. D. W. JOHNSON mentioned a case of intraformational folding and faulting in the Triassic beds of southern Utah, under conditions which suggested slumping on delta front.

Prof. R. D. SALISBURY called attention to crumpled postglacial laminated clays where slumping is not applicable, since the layers now crumpled as to their laminae are themselves horizontal.

Prof. N. M. FENNEMAN: A thick bed of cherty limestone in the Saint Louis formation is brecciated, though included between undeformed beds. Here the chert is so broken as to show sharp corners almost splinters, as though the chert was formed before the deformation of the bed.

Prof. N. H. WINCHELL referred to postglacial crumpled lacustrine beds seen by him in the Mississippi Valley and of similar crumpling in the northern Minnesota in the Archean. The former, he said, he had attributed to the actions of a second ice-sheet crowding and folding previously deposited sediments. Since the announcement by Coleman of the glacial origin of the Archean (Ogishke) conglomerate he had latterly been inclined to assign the latter mentioned crumplings to the same cause, thus showing a possible identical force operating at the extreme ends of the geological scale. He stated that photographic illustrations of the Archean crumpled beds are to be seen in volume IV of his report on the geology of Minnesota.

ILLUSTRATIONS OF THE RECENT EXPOSURE OF THE SARATOGA SPRINGS

BY JOHN M. CLARKE

(Abstract)

The Saratoga Mineral Springs Basin is now the property of the State of New York, and the operations of the State Commission have exposed the fault escarpment very effectively. The views exhibited showed this and also the operations being carried on, partly for the purpose of finding the disappearing or furcated southern extremity of this displacement.

Presented in full without notes.

AN ALTERNATIVE EXPLANATION OF THE ORIGIN OF THE SARATOGA MINERAL WATERS

BY R. RUEDEMANN

(Abstract)

Study of the Saratoga region has led to the theory that the waters come from below the mountain regions to the east, where meteoric waters reach the level of the Ozarkic and Beekmantown limestones. These limestones toward the east are buried, on account of great overthrusts, by an increasing depth of shaly and sandy rocks, and reach there a depth where metamorphism sets in and carbonic acid is produced in the recrystallization of the limestones to silicates. These waters follow the limestone horizon upward and westward, and, on account of the thick shale covering to the northeast, east and south, find the only easy exit around Saratoga near the fault.

Presented in full without notes.

DISCUSSION

Dr. HENRY M. AMI: At the time of the litigation going on referred to by Doctor Ruedemann, the information available on the Saratoga Springs problem respecting the source and origin of the chalybeate waters of that portion of New York State was based to a great extent on records furnished by the diamond-drill core (1,006 feet in length) which the Hon. Senator Hathorn had in his possession and placed at the disposal of the writer. The succession of formations in the fault valley and precise location of the chalybeate waters in the Hathorn well pointed to the occurrence of calcareous and dolomitic strata in the greater depths of the well, the chemical dissolving of which led to the production of CO_2 . The fault blocks of the region appertain to one period, probably the close of the Paleozoic, while the thrust fault to the east must belong to a later period. The work of uncovering the fault in the valley at Saratoga Springs, of redeeming and unrolling the waters, as well as improvement of this wonderful zone of chalybeate waters by the State of New York, is not only most important, but commendable; and, by following the geological structure and indications of nature, will mean much for the whole country.

Adjournment of the section was taken about 5.30 o'clock p. m.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE SECOND SECTION
AND DISCUSSIONS THEREON

The second section met at about 2.30 o'clock p. m., under the chairmanship of President E. A. Smith, and listened to the papers scheduled under Group B: Stratigraphic, Paleontological,⁶ Areal, and Cartographic. E. W. Berry served as secretary of the section.

CHARACTERISTICS OF A CORROSION CONGLOMERATE

BY F. W. SARDESON

(Abstract)

A conglomerate in the Galena limestone formation was described. It consisted of black pebbles in a bluish matrix. The pebbles were a foot and less in width. This conglomerate contained marine fossils, those found in the pebbles being the same as those in the matrix. It is thought to be the result not of erosion by waves, but of corrosion by the sea under conditions that were described. This conglomerate is one of many which are found in the Ordovician and Cambrian of this region. They are all associated with marine faunas, and therefore might be interpreted as evidence of marine recession and transgression, according to the prevailing theory of the present time. Most of them are thought by the author to be of different origin.

Read in abstract from manuscript. The paper was discussed by Messrs. T. W. Vaughan, David White, E. O. Ulrich, and Charles Schuchert.

A PRE-CAMBRIAN UNCONFORMITY IN VERMONT

BY ARTHUR KEITH

(Abstract)

In recent years the west border of the Green Mountains has been examined in search of a possible root for a great thrust fault in the Taconic Mountains which has been described to the Society at its last two meetings. This search has brought to light a broad relation of much importance in the Cambrian and lower beds.

The Cambrian consists of numerous distinguishable formations of limestone, dolomite, and sandstone, the lowest being a mass of quartzite. Fossils of the Olenellus zone are found in the limestones and upper part of the quartzite. Below these is a great thickness of schist, dolomite, graywacke, quartzite, and conglomerate. These lower rocks are separated from the Cambrian by a great unconformity, above which the Cambrian quartzite transgresses the entire lower series. There is abrupt removal of the formations under the unconformity, along which visible breaks of deposition and erosion are seen, and a basal conglomerate, with pebbles of the underlying rocks, lies at the base of

⁶ Purely paleontological papers were referred to the Paleontological Society for reading.

the Cambrian quartzite. The conclusion is reached that these older sediments, bounded above and below by conglomerates and unconformities, are properly classed as Algonkian.

Presented in full without notes. The paper was discussed by Dr. C. D. Walcott.

*RECONNAISSANCE OF THE ALGONKIAN ROCKS OF SOUTHEAST
NEWFOUNDLAND*

BY ARTHUR F. BUDDINGTON⁷

(*Abstract*)

The Algonkian rocks of southeast Newfoundland consist, first, of a thick series of sediments at least 16,000 feet thick; and, second, of a complex of igneous rocks comprising intrusive bosses of granite, syenite, and gabbro, innumerable dikes of basic and acid porphyries, and several lava flows, both basic and acid. The latter are accompanied by equivalent tuffs and agglomerates, and although completely devitrified and more or less sheared, yet are preserved in a remarkably fresh condition. The acid lavas show beautiful spherulitic, lithophysal, flow breccia, fluxion, and ellipsoidal structures. The basic lavas, probably of submarine origin, show a characteristic development of pillow lavas, as well as amygdaloidal and possible variolitic structures. Volcanic necks filled with agglomerate are indicated at one or two places.

The sedimentary series is made up for a large part of more or less water-worn volcanic material and consists of green and purple cherty slate, volcanic conglomerate, purple argillite, and an upper series, 6,000 to 7,000 feet thick, of red and green sandstones, conglomerates, and shales, which in their predominating red color, fresh feldspars, cross-bedding, and intraformational conglomerates show evidence of a continental origin.

Read in full from manuscript. The paper was discussed by Mr. Arthur Keith.

*SECTIONS ILLUSTRATING THE LOWER PART OF THE SILURIAN SYSTEM OF
SOUTHWESTERN ONTARIO*

BY MERTON Y. WILLIAMS⁸

(*Abstract*)

The subject-matter of this article is based on detailed field work done during the past summer for the Geological Survey of Canada and extending along the Niagara escarpment from Niagara Falls to the end of the Bruce Peninsula. Twenty-three important sections were measured.

The conclusions are as follows: The Medina sandstones of Niagara gorge (125 feet thick) are represented farther north by dolomite and shales (cata-ract formation). The members of the Clinton formation, along with the

⁷ Introduced by Gilbert van Ingen.

⁸ Introduced by E. M. Kindle.

Rochester shale, scarcely extend beyond the Niagara Peninsula, the Wolcott limestone alone being seen at a locality of 25 miles northeast of Hamilton. The Lockport dolomite rests from northeast to southeast successively on Medina (catact), Clinton and Rochester formations being thickest in the north. Typical guelph fossils, including *Megalomus canadensis*, were found on the northwestern portion of the Bruce Peninsula.

Read in full from manuscript. The paper was discussed by Messrs. E. O. Ulrich, A. W. Grabau, and John M. Clarke.

*EVIDENCE OF CLIMATIC OSCILLATIONS IN THE PERMO-CARBONIFEROUS
BEDS OF TEXAS*

BY E. C. CASE

(Abstract)

This paper described the general series of deposits in the Wichita and Clear Fork formations of north central Texas and attempts to show how a few of the most persistent of the beds show evidence of a local change in climate. The change in climate is correlated with the invasion of the region by a sea from the south. The evidence from the nature of the deposits is supported by the occurrence of plant and vertebrate fossils.

Read in full from manuscript. The paper was discussed by Prof. A. W. Grabau.

*GEOLOGIC HISTORY OF THE FLORIDA CORAL-REEF TRACT AND COMPARISONS
WITH OTHER CORAL-REEF AREAS*

BY THOMAS WAYLAND VAUGHAN

(Abstract)

The geologic formations of the southern end of the mainland of Florida and of the Florida Keys were briefly characterized, and it was shown that in Pleistocene time chemical deposition which resulted in the formation of oolite was about one hundred times as effective in the formation of limestone as coral reefs. The ratio of the constructional work of chemical deposition in Pleistocene time in Andros Island, Bahamas, to that of the living barrier reef off the east side of that island was stated to be several thousand to one.

The living barrier reef of Florida occurs within the 10-fathom curve on a platform the geographic limits of which exceed those of the reef, thus showing that the reef is superimposed on a platform built by other than reef agencies.

As several students of coral reefs have attributed the formation of atolls to submarine solution by virtue of the carbon dioxide content of flowing seawater, this subject was studied from four standpoints, and the conclusion definitely reached that submarine solution has not been instrumental in the formation of the bays, sounds, and lagoons of the Florida coral-reef tract. The atoll rims of both the Tortugas and Marquesas have been shaped by winds and currents.

The Marquesas are Recent in geologic age. The Tortugas were outlined during Pleistocene submergence after an interval of uplift following Pliocene deposition; after these events there was a second period of uplift, and after it a second period of depression. The modern corals and the surface detritus of the Tortugas rest on an older foundation shaped for them during an antecedent period of submergence.

The elevated barrier reef of Florida was formed during subsidence following uplift subsequent to the close of Pliocene time. After its formation the reef tract was elevated about 50 feet. This elevation was followed by depression and the present barrier formed seaward of the older one on a platform already prepared for it. These conditions simulate those found on Andros Island, Bahamas, and in Cuba. In the Bahamas, instead of an older Pleistocene reef, there is Pleistocene oolite.

The oscillations of sealevel in Florida and around Andros Island were without notable tilting or flexing of the preceding deposits, while there was decided differential crustal movement preceding the last depression in Cuba, where the terraces rise higher at the eastern end than westward, and those on the north coast west of the longitude of Manzanillo stand higher than those on the south coast.

As atolls are solely constructional geologic phenomena, Agassiz's "old ledge" in the atolls of the Pacific belongs to a previous physiographic cycle, and the Recent corals are growing on an older foundation. There was in the Pacific a great development of coral reefs, including atolls, in Pleistocene (perhaps late Tertiary) time, antecedent to the Recent reef development. These earlier reefs have been subjected to differential crustal movement, so that certain areas (as Makatea, Paumotu, Mango, Fijis, etcetera) have been lifted above sealevel; others remain at about sealevel (Rangiroa), while in other areas (or in other parts of the same area) there has been depression (Bora Bora). The Pacific island groups have not oscillated as units, but have undergone differential crustal movement.

The data presented on the relations of the barrier reefs of Florida, Bahamas, Cuba, and Australia showed that all of them stand on platforms submerged by rise of strand-line, and that the platforms are independent of the limits of living reefs. It is evident that the reefs are superimposed on platforms formed by other than reef agencies, and that reef-building organisms grow only in those places on the platforms where conditions for their life are favorable. The barrier reefs of Viti Levu, Fijis, and Tahiti, Society Islands, are similar in their relations—that is, they are superimposed on depressed platforms, the presence of which is independent of the reefs.

The accordance in depth of the barrier-reef lagoons of Australia, the Society Islands, etcetera, with that of the lagoons of oceanic atolls was indicated. Attention was directed to the comparative crustal stability of the Bermuda Islands and of the Paumotuian atoll region, and the conclusion expressed that great crustal subsidence in atoll areas is not indicated by the facts at present available.

Read in full from manuscript.

The section adjourned about 5.30 o'clock p. m.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE THIRD SECTION
AND DISCUSSIONS THEREON

The third section convened about 2.30 o'clock p. m., with Vice-President James F. Kemp serving as chairman and Heinrich Ries as secretary. The section took up the reading of papers in Group C as follows: Petrologic, Mineralogic, and Economic:

GRAPHIC METHOD OF REPRESENTING THE CHEMICAL RELATIONS OF A
PETROGRAPHIC PROVINCE

BY FRANK D. ADAMS

The paper described a method by which the results of individual analyses, after having been plotted in the form of curves, may be combined, so that a warped surface is obtained on which are expressed the chemical relationships of the rocks of an entire petrographic province.

Read in full from manuscript.

DISCUSSION

Prof. JAMES F. KEMP: The curves of the oxides are fairly uniform in the case of alumina and the alkalies. They showed the chief ups and downs in the cases of magnesia and lime. The question was raised if the speaker had drawn any conclusions from the regular or irregular distribution of the components.

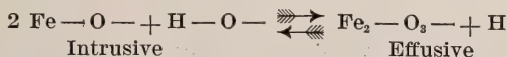
Further remarks were made by the author.

EFFUSIVE AND INTRUSIVE IN THE QUANTITATIVE CLASSIFICATION

BY ALFRED C. LANE

(Abstract)

Ludwig has made experiments to show that at high pressures (6,000 to 3,000 atm.) Al and Bi become bivalent instead of trivalent. If this be true for Fe, then:



Intrusive

Effusive

a reaction confirmed by the fact that the average analysis of gabbro (Daly) contains more ferrous iron than the average basalt, and by the fact that the ferrous or hydroxyl-containing components of gabbro appear as brotocrystals in basalt.

According to Rule (7) for calculating norm, every molecule of ferric iron means three of Fe which might otherwise be combined with SiO_2 . Thus if the norm contains free silica, three molecules of free silica might be combined as femic, or 9 per cent SiO_2 , for each 8 per cent Fe_2O_3 transferred from Q to FEM. Thus identically the same chemical magma may as an effusive be

found in a different order (especially Order 4 instead of 5), and even class (II instead of III), than as an intrusive without magmatic differentiation.

Presented by title in the absence of the author.

*CHANGE IN THE CRYSTALLOGRAPHICAL AND OPTICAL PROPERTIES OF
QUARTZ WITH RISE IN TEMPERATURE*

BY FRED E. WRIGHT

(Abstract)

A brief description of the methods and results of measuring the change in the crystal angles and the optical properties of quartz to 1,250° C., the purpose of such measurements being to gather information on the character and order of magnitude of the crystal forces themselves. A crystal may be considered a system of forces which exerts a definite influence on any external system of forces (as that producing light waves) with which it is brought in contact. On heating the crystal slight changes are produced in the crystal system of forces, and these in turn produce slight changes in second system. The equation expressing the relation between these slight (differential) changes in the two systems is a differential equation which on integration states the relations between the original system. The results obtained thus far on quartz were presented briefly from this viewpoint.

Presented in abstract without notes.

DISCUSSION

Prof. O. C. FARRINGTON asked Doctor Wright for his definition of crystal.

Doctor WRIGHT replied as follows: The term crystal was applied first by the Greeks to clear quartz crystals on the assumption that such crystals had been formed from water by the action of a "long and vehement cold," thus producing a kind of ice which did not melt easily.

*MODE OF FORMATION OF CERTAIN GNEISSES IN THE HIGHLANDS OF NEW
JERSEY*

BY C. N. FENNER

(Abstract)

The paper relates to the structure and mode of origin of certain pre-Cambrian gneisses in northern New Jersey. A description is given of the field relations in a certain area near Pompton, where favorable conditions for observation have been found. The structures shown here are believed to be typical for considerable areas in this portion of the State. Evidence is found leading to the belief that the origin of the banded gneisses at this locality is to be attributed to the injection of a thinly fluid granitic magma between the layers of an original laminated rock, which carried large amounts of hornblende or biotite. Structures which still survive in the associated bodies of granite indicate that the process of injection was carried on in a most quiet and gradual manner, and possessed many of the characteristics of a substitu-

tion of the original material by the magmatic solution rather than those of a violent intrusion. The observed relations are very similar to those which foreign geologists have described as due to lit-par-lit injection, and the mode of operation is believed to have been essentially the same.

Certain features observed in the gneisses imply characteristics of the magma which at first sight do not appear mutually concordant. Thus the degree of viscosity implied by the presence of thinly tabular sheets of inclusions within the granite, standing nearly upright and unsupported except by the magma on either side, does not harmonize with the facility with which magmatic material has been transfused into the adjacent rock. In trying to reconcile these apparently antagonistic features inquiry has been directed toward a consideration of certain of the properties of magmatic solutions. The question of the critical temperatures of volatile substances is discussed in its bearing on their condition within the magma. Further, the problem of a possible differentiation of a magma when injected into a wall rock in a multitude of adjacent streams is taken up, as related to the views expressed by the foreign advocates of lit-par-lit injection. On this matter our knowledge of the physical and chemical properties of magmas is deficient in so many respects that very positive statements can not be made, but it appears that under the conditions of injection such a differentiation as has been assumed would probably take place. By this means the advance of the main body of magma would be preceded by that of a more dilute portion, which would be able to impregnate the wall rock with facility and initiate processes of transformation and solution which the more concentrated body following would carry farther toward completion.

Read in full from manuscript.

DISCUSSION

Dr. J. V. LEWIS: In my experience in the New Jersey Highlands it has seemed that two distinct types of parallel structure exist there—this lit-par-lit injection which Doctor Fenner has brought out so interestingly and an indistinct gneissic appearance which some of us have thought of as perhaps a sort of internal flow-structure. I should like to ask Doctor Fenner whether it is possible to make this distinction in the region of his studies.

Further remarks were made by Messrs. J. P. Iddings and James F. Kemp.

MAGMATIC DIFFERENTIATION AND ASSIMILATION IN THE ADIRONDACK REGION

BY WILLIAM J. MILLER

(Abstract)

The deep-seated condition to which the present surface rocks of the pre-Cambrian area in northern New York were subjected when the tremendous molten masses were intruded into the thick Grenville sediments were decidedly favorable for both magmatic differentiation and assimilation. Probably few regions present any better opportunities for the study of such phenomena. It

was the purpose of this paper to briefly summarize the more important observations made by the writer during the past eight years bearing on these problems.

Viewed in the broadest way, the great masses of plutonic rocks, excluding the anorthosite, show all sorts of gradations back and forth, from gabbro and diorite to granite and granite porphyry, with a quartz syenite the prevailing type. In this connection the possible presence of a great intrusive (so-called "Laurentian granite") older than the syenite in the Adirondack region will be discussed.

Besides the above-mentioned plutonic rocks, there are an almost endless number and variety of rocks which are neither simple intrusives nor true Grenville, but which are distinctly intermediate in character.

Evidence was presented to show that the broader variations among the unquestioned intrusives is due to differentiation practically unaccompanied by assimilation; that more locally, though often to a considerable extent, pretty complete assimilation of Grenville gneisses by the syenitic and granitic magmas has produced many rocks of intermediate character, and that in very many cases the magmas enveloped Grenville gneiss fragments and either fused only their edges or left them completely undissolved.

Read in abstract from manuscript.

DISCUSSION

Dr. FRANK D. ADAMS: The phenomena described by Messrs. Fenner and Miller are identical with those displayed in the Laurentian-Grenville areas as the margin of the Canadian shield in Canada. In the Haliburton and Bancroft areas of eastern Ontario it is possible to definitely prove that the dark inclusions in the gneissic granite of the batholith are in very many cases at least fragments of the wall rock which have been torn off the invading rock. There is strong presumption that the similar fragments found in the inner portions of the batholiths are derived from the roof of the batholith. Only in a very few places in that great region of 4,500 square miles could proof be secured that an actual solution of its wall rock in the granite magma had taken place, and these areas were of very limited extent.

Mr. SIDNEY PAIGE: A pegmatitic batholith in the Black Hills, South Dakota, throws light on the mechanics of granite intrusions in general. The tentative conclusion has been reached that the intrusion has entered by virtue of its ability to deform a series of previously metamorphosed sediments, to form in these sediments close recumbent folds, and to inject these sediments along the new schistosity developed. Lit-par-lit injection combined with actual mass deformation of the schists are the mechanical elements involved. Stopping on any but a small scale is absent. Assimilation is confined to the immediate borders of the granite contact and is believed to be lit-par-lit injection on a minute scale plus solution of the schist. The introduction of the granite in the layers of the schists is a move in the direction of bringing the schists and granite to equal specific gravities, and this mitigates against the sinking of stoped blocks.

Further remarks were made by Professor Kemp.

NEW POINT IN THE GEOLOGY OF THE ADIRONDACKS

BY J. F. KEMP

(Abstract)

Recent field observations for the New York State Geological Survey in the vicinity of the Keene Valley have shown in massive anorthosite many inclusions of strongly foliated gneiss. The foliation of the fragments runs in all directions, even in an area of a few square yards. The inference will be drawn that the Grenville gneisses were already strongly metamorphosed when the anorthosites entered, and that they are very much older than the intrusives.

Presented in abstract without notes.

DISCUSSION

Prof. W. J. MILLER: Is it not conceivable that the fragments caught up by the anorthosite magma were unaltered sediment and that the inclusions became metamorphosed by the heat of the intrusive?

Further remarks were made by Dr. T. C. Brown.

MINERALS FROM THE ORE DEPOSITS AT PARK CITY, UTAH

BY FRANK R. VAN HORN

(Abstract)

During the month of June, 1911, a short time was spent studying the ore deposits at Park City, Utah. At this visit a considerable number of ore specimens were obtained which have since been examined. These investigations show the presence of considerable amounts of bournonite (Pb Cu_2), $\text{Sb}_2 \text{S}_6$. This fact has never been reported, which is probably due to the similarity of this mineral to tetrahedrite, with which it has probably been confused. The author has found the mineral both at the Silver King and Daly West mines. Calamine, $\text{H}_2 \text{Zn}_2 \text{SiO}_6$, was also found at the Quincy mine and has not been previously reported from the district. Jamesonite, $\text{Pb}_2 \text{Sb}_2 \text{S}_6$, has been rather doubtfully reported, but the writer has found it in notable amounts, and has obtained an analysis of this mineral as well as that of bournonite.

Presented in abstract without notes.

DISCUSSION

Mr. T. T. READ: This interesting study of the tetrahedrite, which proved to be bournonite, induces me to draw attention to a similar experience in the copper deposits of Chile, which are familiar to all of us as the "ancestral home" of a number of unusual minerals. It has been generally supposed that atacamite here occurs widespread in considerable amount. The more careful investigation consequent upon the development of a successful leaching process at Chuquicamata has disclosed the fact that what was there supposed to be

atacamite was in reality brochantite, the amount of atacamite actually present being extremely subordinate. The engineers connected with this enterprise have told me that since having the benefit of this intensive study they have examined the material in one or more large mineral collections and have been able to detect that much of the material shown as atacamite is really brochantite, which closely resembles atacamite at times.

Further remarks were made by Messrs. J. F. Kemp and O. C. Farrington.

DEEPEST BORING IN WEST VIRGINIA

BY I. C. WHITE

(Abstract)

This boring is located on Slaughter Creek, Kanawha County, about one mile south of the Kanawha River from Chelyan, and was sunk to a depth of 5,595 feet by the Hon. Wm. Seymour Edwards, who has generously placed its record at the service of science. It begins near the middle of the Kanawha series of coals, at 490 feet below the Kanawha Flat flint, or about 1,300 feet under the horizon of the Pittsburgh coal. The well penetrated the Corniferous limestone at 4,945 feet, the Oriskany sandstone at 5,035, and stopped in limestone (probably Niagara) at 5,595, just below a large flow of salt water.

Presented in abstract without notes.

The section adjourned about 5.30 o'clock p. m.

PRESIDENTIAL ADDRESS

At 8 o'clock p. m., at the Nassau Club, Prof. Eugene A. Smith delivered his address as retiring President, his topic being

PIONEERS IN GULF COASTAL PLAIN GEOLOGY

Published as pages 157-178 of this volume.

The address was followed by the complimentary smoker given in honor of the Geological Society of America, the Paleontological Society, and the Association of American Geographers by the local members of the three organizations.

SESSION OF WEDNESDAY, DECEMBER 31

The Society convened at 9.42 o'clock a. m. in general session, President Eugene A. Smith in the chair.

REPORT OF COMMITTEE ON PHOTOGRAPHS

The only item to report in connection with the collection of photographs is that it has been moved with me from the Bureau of Mines to my office in the United States Geological Survey. No additions have been offered during the year, but several persons have looked over the collection to find material for illustrating lectures or memoirs.

N. H. DARTON,
Committee.

The report was accepted and the committee was continued.

REPORT OF COMMITTEE ON GEOLOGICAL NOMENCLATURE

The secretary of the committee has received no requests for information or decision, and no action regarding geologic nomenclature has been taken by the committee during the past year.

ARTHUR KEITH,
Secretary.

The report was accepted and the committee was continued.

REPORT OF AUDITING COMMITTEE

The undersigned have examined the vouchers, checks, accounts, and bank book of the Treasurer of the Society and find them correct.

The Securities of the Society, now in a safe-deposit vault in Baltimore, will be examined later by one or more members of the Committee.⁹

Respectfully submitted.

EDWARD B. MATHEWS,
U. S. GRANT,
T. WAYLAND VAUGHAN,
Committee.

The report was accepted.

AMENDMENT TO THE BY-LAWS

In accordance with the notice which had been sent out by the Secretary, the following amendment to By-Laws was submitted:

Chapter 1, paragraph 1, add the sentence: "A Fellow in good standing, however, who has paid annual dues for not less than fifteen (15) years

⁹ Under date of February 10, 1914, Edward B. Mathews reports that, acting as a member of the Auditing Committee of the Society, he examined the Society's securities in the hands of the Treasurer and found them to be as listed in the Treasurer's report under date of December 1, 1913.

may commute further dues and become a Life Fellow by making a single payment of one hundred (100) dollars."

On motion, it was voted to adopt this amendment to the By-Laws.

The Secretary announced that, in view of changes made, a revision of the "Constitution and By-Laws" and "Publication Rules" of the Society would be included in the Proceedings Brochure.

BIBLIOGRAPHY OF FORMATION NAMES

For the information of the fellowship, the Secretary read the following letter which had been received by him:

"In response to your inquiry of December 22, concerning the publication of all the names applied to geological formations in the United States:

"Your request evidently concerns the revision and enlargement of Bulletin 191 to include all formation names up to date. For several years the Survey has endeavored to make as complete as possible the indexing of geological formation names in the American literature, and I am happy to be able to say that the task is approaching completion. Meanwhile, however, the bibliographies issued annually have given to the public nearly all of the material collected, so that the information is for the most part now available in the bibliographic bulletins of the Survey. On this account, and because the publication of all the material in hand in one bulletin would require printing a volume estimated at about three times the size of Bulletin 191, which is a volume of 448 pages, I have hesitated, in view of the very numerous claims on the publication fund—some of which have appeared more urgent than a complete catalogue of the formation names—to put the matter into print. The funds available for publication during the current year are already overtaxed.

"I shall be very glad to be advised by geologists as to their estimate of the need and value of the proposed publication. It should be borne in mind that Bulletin 191 is still available through purchase from the Superintendent of Documents, Washington, D. C., the price being 25 cents. Those of the annual bibliographies that are no longer available for free distribution are obtainable from the same source.

"Possibly not all geologists are aware that the geological formation indexes, in card form, are at all times available for consultation in this office, and that inquiries by mail as to whether any given name is preoccupied, or as to the original place of publication or definition of any name, are given prompt and full attention. It is my desire to make these data of the greatest use to all geologists.

"Yours very truly,

"(Signed)

GEO. OTIS SMITH,

"Director, U. S. Geological Survey."

The Secretary then presented in printed form the annual report of the Council as follows:

REPORT OF THE COUNCIL

To the Geological Society of America, in twenty-sixth annual meeting assembled:

The regular annual meeting of the Council was held at New Haven, Conn., in connection with the meeting of the Society, December 28 to 31, 1912.

The details of administration for the twenty-fifth year of the existence of the Society are given in the following reports of the officers:

SECRETARY'S REPORT

To the Council of the Geological Society of America:

Meetings.—The proceedings of the annual general meeting of the Society held at New Haven, Conn., December 28-31, 1912, have been recorded in volume 24, pages 1-90; of the Cordilleran Section, pages 91-98, and of the Paleontological Society, pages 99-132, of the Bulletin.

Membership.—During the past year the Society has lost one Fellow by death, William M. Fontaine; and one Correspondent, Hermann Credner. Two Fellows have been dropped for non-payment of dues. The names of seventeen out of nineteen Fellows elected at the Washington meeting have been added to the list, two of them having failed to qualify. The present enrollment of the Society is 356. Twelve candidates for fellowship are before the Society for election and several applications are under consideration by the Council.

Distribution of Bulletin.—There have been received during the year 10 new subscriptions to the Bulletin, 5 subscriptions have been discontinued, making the number of subscribers 114.

The irregular distribution of the Bulletin during the past year has been as follows: Complete volumes sold to the public, 58; sold to Fellows, 1; sent out to supply deficiencies, 2, and delinquents, 2; brochures sent out to supply deficiencies, 6, and delinquents, 134; sold to Fellows, 14; sold to the public, 28.

Bulletin Sales.—The receipts from subscriptions to and sales of the Bulletin during the past year are shown in the following table:

Bulletin Receipts, December 1, 1912–November 30, 1913

	Complete volumes.			Brochures.			Grand total.
	Fellows.	Public.	Total.	Fellows.	Public.	Total.	
Volume 1.....		\$22.50	\$22.50				\$22.50
Volume 2.....		22.50	22.50				22.50
Volume 3.....		22.50	22.50				22.50
Volume 4.....		22.50	22.50	\$0.15		\$0.15	22.65
Volume 5.....		22.50	22.50	.25		.25	22.75
Volume 6.....		22.50	22.50				22.50
Volume 7.....		22.50	22.50				22.50
Volume 8.....		30.00	30.00		\$0.80	.80	30.80
Volume 9.....		30.00	30.00				30.00
Volume 10.....		37.50	37.50	.60		.60	38.10
Volume 11.....		30.00	30.00				30.00
Volume 12.....		30.00	30.00	.15	.60	.75	30.75
Volume 13.....		37.50	37.50	1.25	2.70	3.95	41.45
Volume 14.....		30.00	30.00		3.00	3.00	33.00
Volume 15.....		22.50	22.50	.75		.75	23.25
Volume 16.....		22.50	22.50				22.50
Volume 17.....		22.50	22.50	.10	2.50	2.60	25.10
Volume 18.....		15.00	15.00				15.00
Volume 19.....		22.50	22.50		1.20	1.20	23.70
Volume 20.....		22.50	22.50		3.00	3.00	25.50
Volume 21.....		22.50	22.50		3.80	3.80	26.30
Volume 22.....		22.50	22.50	1.50	24.70	26.20	48.70
Volume 23.....	\$7.50	60.00	67.50	4.05	8.15	12.20	79.70
Volume 24.....		712.50	712.50		.45	.45	712.95
Volume 25.....		22.50	22.50				22.50
Total...	\$7.50	\$1,350.00	\$1,357.50	\$8.80	\$50.90	\$59.70	\$1,417.20
Index 1-10.....		9.00	9.00				9.00
Index 11-20.....	3.50	24.50	28.00				28.00
Total...	\$11.00	\$1,383.50	\$1,394.50	\$8.80	\$50.90	\$59.70	\$1,454.20

Receipts for the fiscal year..... \$1,454.20
 Previously reported..... 15,558.21

Total receipts to date..... \$17,012.41
 Charged, but not yet received: On 1911 account..... 7.50
 On 1912 account..... 13.90
 On 1913 account..... 48.40

Total sales to date..... \$17,082.21

Four subscriptions to volume 24 are still to be paid for and 8 of the regular subscribers have not yet sent in their orders for the volume. No volumes are sent out now except on definite orders.

Expenses.—The following table gives the cost of administration and of Bulletin distribution during the past year:

EXPENDITURE OF SECRETARY'S OFFICE DURING THE FISCAL YEAR ENDING NOVEMBER
30, 1913*Account of Administration*

Postage	\$50.52
Printing and stationery.....	85.30
Express	3.44
Telephone charges.....	2.65
Telegrams	1.62
Binding three copies of Bulletin.....	4.80
Addressograph plates.....	.91
Engrossing certificates.....	2.25
Cordilleran Section (1912 and 1913).....	36.51
Total.....	\$188.00

Account of Bulletin

Postage and express.....	\$43.47
Collection charges on checks.....	1.65
Drawings for Bulletin.....	9.00
Reimbursement to 69 Fellows on account of payments made for the Index to Vols. 11-20 ¹⁰	241.50
Total.....	295.62
Total expenditures for the year.....	\$483.62

Respectfully submitted.

EDMUND OTIS HOVEY,
*Secretary.*NEW YORK, *December 18, 1913.*

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his annual report for the year ending December 1, 1913.

The membership of the Society at the present time is 356, of whom 93 are Life Members, while 263 pay annual dues. Nineteen new members were elected at the last annual meeting, 17 of whom qualified. Two members were dropped from the roll for the non-payment of dues and 1 member died. Fifteen members are delinquent in the payment of dues—2 for four years and therefore liable to be dropped from the roll—5 for two years and 8 for one year.

¹⁰ By vote of the Council at the New Haven meeting.

With the advice of the Investment Committee, the Treasurer bought during the year two Chicago Railway Company first mortgage five per cent bonds at a cost of \$1,947.50, with interest.

The Society owns at the present time the following securities:

RECEIVED FROM THE FORMER TREASURER

Par value		Date of purchase
\$2,000	Texas and Pacific Railroad Company first-mortgage five per cent bonds, due June 1, 2000	March 17 and 25, 1908
1,000	(10 shares) Iowa Apartment House Company, Washington, D. C., stock ¹¹	February 6, 1901
2,000	(20 shares) Ontario Apartment House Company, Washington, D. C., stock ¹²	April 7, 1903
3,000	United States Steel Corporation second-mortgage five per cent bonds, due April 1, 1963..	April 11, 1904
1,000	(10 shares) Ontario Apartment House Company, Washington, D. C., stock ¹²	May 12, 1905
1,000	(10 shares) Ontario Apartment House Company, Washington, D. C., stock ¹²	March 24, 1906

PURCHASED BY THE PRESENT TREASURER

Par value		Date of purchase
1,000	St. Louis, Iron Mountain and Southern Railway Company five per cent equipment bond, due June 1, 1915.....	February 5, 1908
1,000	St. Louis and San Francisco Railroad Company five per cent equipment bond, due February 1, 1919.....	December 6, 1910
2,000	Fairmont and Clarksburg Traction Company first-mortgage five per cent bonds, due October 1, 1938.....	November 8, 1911
2,000	Consolidation Coal Company first and refunding mortgage five per cent sinking-fund gold bonds, due December 1, 1950.....	November 5, 1912
2,000	Chicago Railways Company first-mortgage five per cent bonds, due February 1, 1927.	November 28, 1913

\$18,000—Total

¹¹ Dividends at the rate of 5 per cent are paid on this stock.

¹² Dividends at the rate of 5 per cent were paid on this stock to July, 1909, after which date no dividends were paid until January, 1912, when dividends were resumed at the rate of 4 per cent.

TREASURER'S REPORT

55

RECEIPTS

Balance in the treasury December 1, 1912.....	\$1,241.50
Fellowship fees, 1911 (2).....	\$20.00
1912 (3).....	30.00
1913 (246½).....	2,465.00
1914 (3).....	30.00
	2,545.00
Initiation fees (17).....	170.00

Interest on investments:

Iowa Apartment House Company stock...	\$50.00
Ontario Apartment House Company stock.	160.00
Texas & Pacific Railroad bonds.....	100.00
U. S. Steel Corporation bonds.....	150.00
St. Louis, Iron Mountain and Southern Railway bond.....	50.00
St. Louis and San Francisco Railroad equipment bond.....	50.00
Fairmont and Clarksburg Traction bonds.	100.00
Consolidation Coal Company bonds.....	100.00
Interest on deposits, Baltimore Trust Co..	89.06
	849.06

Case Library, accessions 1911, 1912.....	300.00
Collection charges added to checks.....	.40

Received from Secretary:

Sales of publications.....	\$1,454.20
Authors' separates.....	151.30
Authors' corrections.....	8.15
Collection charge added to check.....	.10
Binding one volume of Bulletin.....	1.50
	1,615.25
	\$6,721.21

Secretary's office:

EXPENDITURES

Administration	\$188.00
Bulletin	295.62
Secretary's allowance.....	700.00
	\$1,183.62

Treasurer's office:

Postage, bond, safe-deposit box.....	\$43.00
Allowance for clerical hire.....	50.00
	93.00

Publication of Bulletin:

Printing ¹³	\$2,031.12
Engraving	153.82
Editor's allowance.....	250.00
	2,434.94

Purchase of two Chicago Railways Company five per cent bonds, with interest.....	1,980.00
Balance in bank December 1, 1913.....	1,029.65
	\$6,721.21

Respectfully submitted.

WM. BULLOCK CLARK,
Treasurer.

BALTIMORE, MD., *December 1, 1913.*

EDITOR'S REPORT

To the Council of the Geological Society of America:

The Editor submits herewith his annual report. The following tables cover statistical data for the twenty-four volumes thus far issued:

Cost.	Average— Vols. 1-20.	Vol. 21.	Vol. 22.	Vol. 23.	Vol. 24.
	pp. 610. pls. 55.	pp. 839. pls. 54.	pp. 759. pls. 31.	pp. 774. pls. 43.	pp. 755. pls. 36.
Letter press....	\$1,686.58	\$2,049.95	\$1,660.45	\$1,750.40	\$1,647.90
Illustrations....	390.99	404.27	260.81	274.70	288.80
	\$2,077.57	\$2,454.22	\$1,921.26	\$2,025.10	\$1,936.70
Average per page...	\$3.41	\$2.93	\$2.53	\$2.62	\$2.56

¹³ This item includes transportation charges on the regular distribution of the Bulletin	\$30.97
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Authors' separates in excess of number given gratis by the Society.....	151.30
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Classification.

Volume.	Areal geology.	Physical geology.	Glacial geology.	Physiographic geology.	Petrographic geology.	Stratigraphic geology.	Paleontologic geology.	Economic geology.	Official matter.	Memorials.	Unclassified.	Total.
Number of pages.												
1.....	116	137	92	18	83	44	47	.....	60	4	4	593+xii
2.....	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3.....	56	41	44	41	32	158	104	.....	61	15	1	541+xii
4.....	25	134	38	74	52	52	14	.....	47	32	2	458+xii
5.....	138	135	70	54	28	51	107	.....	71	14	9	665+xii
6.....	50	111	75	39	71	99	1	.....	63	25	4	538+x
7.....	38	77	105	53	40	21	123	4	66	28	13	558+x
8.....	34	50	98	5	43	67	58	14	79	8	.....	446+x
9.....	2	102	138	.....	44	28	64	16	64	12	.....	460+x
10.....	35	33	96	37	59	62	68	28	84	27	17	534+xiii
11.....	65	110	21	10	54	31	188	7	71	60	46	651+xii
12.....	199	39	55	53	24	98	5	5	70	2	.....	538+xi
13.....	125	17	13	24	28	116	42	4	165	32	29	583+xii
14.....	48	47	48	59	183	118	22	1	80	14	1	609+xi
15.....	26	124	3	94	36	267	.....	.....	77	17	3	636+x
16.....	64	111	78	30	102	141	19	.....	67	22	15	636+xiii
17.....	49	161	41	84	47	294	27	.....	71	9	2	785+xiv
18.....	16	164	141	5	29	246	5	.....	68	40	3	717+xii
19.....	106	108	29	66	30	155	32	.....	56	15	20	617+x
20.....	43	54	35	29	37	45	303	8	60	3	132	749+xiv
21.....	72	234	75	48	85	70	106	1	111	11	10	823+xvi
22.....	23	54	28	28	23	403	74	.....	63	49	1	747+xii
23.....	75	52	126	108	19	145	134	.....	66	32	1	758+xvi
24.....	18	57	96	57	49	160	106	23	133	53	3	737+xviii

Respectfully submitted.

JOSEPH STANLEY-BROWN, *Editor.*COLDSPRING HARBOR, N. Y., *December 15, 1913.*

On motion, the report was laid on the table.

The Society then proceeded, at 9.50 o'clock a. m., to the consideration of scientific papers.

TITLES AND ABSTRACTS OF PAPERS PRESENTED IN GENERAL SESSION AND
DISCUSSIONS THEREON*IMPROVEMENTS IN METHODS OF INVESTIGATING HIGHLY CARBONIZED
MATERIALS AND THEIR BEARING ON THE MODE OF DEPOSITION OF
COAL*BY EDWARD CHARLES JEFFREY ¹⁴*(Abstract)*

By radically new methods of procedure, which have been developed as the result of long experiment, it has been found possible to secure transparent sections of the hardest and most highly carbonized anthracites. The results are of considerable interest as showing the mode of formation of coal in general and particularly of anthracites. The present communication deals particularly with the anthracitic coals of Pennsylvania, although anthracitic coals of widely different geographical areas and geological horizons have likewise been studied.

Presented by title in the absence of the author.

*ORIGIN OF OOLITES AND THE OOLITIC TEXTURE IN ROCKS*BY THOMAS CLACHAR BROWN ¹⁵*(Abstract)*

A brief historical review of the study of oolites was given, including references to the earliest published papers, the theories of organic origin, the theories of chemical origin, and the artificial production of oolites.

The microscopic structure of oolites was described as follows: Recent oolites from Salt Lake; calcareous oolites from the Cambrian and Ordovician; dolomitic oolites from the Ordovician; siliceous oolites from the Ordovician and Tertiary; Clinton oolitic iron ore from the Silurian.

An argument was then advanced to show that all of these oolites are of chemical origin, formed, first, as calcareous oolites, and then changed by replacement to their present condition.

Presented in abstract from notes.

DISCUSSION

Dr. C. A. DAVIS: In work on the formation of Chara marls in Michigan it was found that the Ca CO_3 was precipitated from water which was not saturated with Ca CO_3 , and that segregation by plants was essential in the formation of the deposit. This segregation was selective for the calcium and magnesium and neglected dissolved iron compounds also in the water in considerable quantity.

¹⁴ Introduced by David White.¹⁵ Introduced by Florence Bascom.

Dr. A. M. MILLER: There exists in Bath County, Kentucky, a remarkable deposit of oolitic carbonate of iron which is evidently a replaced Devonian limestone, the oolitic structure therefore being a phenomenon accompanying chemical replacement of an already consolidated lime sediment.

Mr. T. W. VAUGHAN expressed pleasure in Professor Brown's presentation of the subject of the formation of oolites. The Bahamas and Florida offer an advantageous field for study of the origin of oolites, as the formation of oolite grains can be observed in the chemically precipitated calcareous muds so abundant there. Mr. Vaughan said that as in his opinion the formation of oolites from chemically precipitated calcium carbonate is established, attention should now be especially directed to the discovery of the agencies whereby chemical precipitation is effected. Two classes of bacteria, the denitrifying and sulphate-reducing, are such agents. Drew's work in the Bahamas showed that there are off the western shore of Andros Island as many as 160,000,000 denitrifying bacteria to the cubic centimeter. It was mentioned that Dr. Carl F. Kellerman, of the Bacteriological Laboratory of the United States Department of Agriculture, had undertaken an investigation of the bacterial flora of Great Salt Lake for the purpose of ascertaining what role bacteria may there play in the precipitation of calcium carbonate, and that he had consented to make additional researches on the bacteria of the muds and the waters of southern Florida and the Bahamas.

Further remarks were made by Dr. Chester A. Reeds.

PRECISE LEVELING AND THE PROBLEM OF COASTAL SUBSIDENCE

BY DOUGLAS W. JOHNSON

(Abstract)

Precise leveling recently completed in New Jersey and New York throws some light on the question as to whether or not this part of the Atlantic coast is undergoing progressive subsidence. The work in southern New Jersey shows that there has been no differential tilting or warping of the coast during the 25 years from 1886 to 1911. Similar investigations in the vicinity of New York city also show a total absence of any differential movement during 24 years, from 1887 to 1911. The surveys further show that the position of mean sealevel has remained the same for 24 years at least. Taken together, these facts prove remarkable stability of the portion of our coast supposed to show the most pronounced evidences of continued subsidence and corroborate the physiographic evidence of long-continued stability.

Presented in full without notes.

DISCUSSION

Prof. WILLIAM H. HOBBS: The bearing of all earthquake study seems to show that vertical movements of a coastline are interrupted rather than gradual and uniform. It is therefore quite possible that for a period of 25 years no movement would be registered, but might yet be followed by a very considerable adjustment of level in the succeeding years.

Prof. J. W. SPENCER: In 1894, based on what proved to be erroneous data on a map, I suggested the present continuance of earth movements in the region of Lake Erie. This hypothesis was elaborated into a good monograph (United States Geological Survey, number 18) by Dr. G. K. Gilbert by the use of selected later levels. Since then I have taken all the daily fluctuations of the Erie levels and find that since 1854 there have been no differential earth movements, which result may be correlated with Doctor Johnson's results relating to the Atlantic coast.

Prof. ELLSWORTH HUNTINGTON: I should like to ask Doctor Johnson two questions. As to the first, I may be laboring under some misapprehension. His data seem to show conclusively that in his area there has been no differential movement during the last 25 years. Does this prove anything as to general movements of the entire area? The whole region, covering a distance of a hundred miles or more, might have been depressed 2 or 3 inches, but measurements of the type here described would not show it, for all the points of observation would sink equally. The second question relates to certain recent discoveries reported from Boston. The newspapers state that a fish weir has been discovered 18 feet below the present high-tide level and 12 feet below low-tide level. How does this bear on the present conclusions?

Dr. G. P. MERRILL spoke of the gradual encroachment of the sea as illustrated by the undermining of stone walls and erosion of the soil on the northern, western, and southern margins of a small island in Sheepscot Bay, Maine. Of the three points of observation but one faced the open sea. He felt, therefore, that the erosion could not be due to temporary conditions, as a few seasons of exceptional storms, and while not claiming that it indicated an actual sinking of the coast, felt that it unquestionably did indicate a change in conditions over those existing at a period not more remote than 25 to 30 years.

Prof. D. W. JOHNSON, replying to the points raised by the different speakers, said that the evidence which he had just presented proved coastal stability along one portion of the Atlantic coast for a quarter of a century only. The evidence for coastal stability for a much greater period was abundant, and had been presented in part at two previous meetings of the Society. It will not do to assume that some parts of the coast are rising and others sinking, since apparent indications of both elevation and depression occur at points on the coast which can be shown to be stable, and any adequate theory must take all these facts into consideration and satisfactorily explain them. The theory of essential coastal stability, with local fluctuation in high-tide levels does this. The evidence furnished by the precise levels cannot be explained, as one speaker suggests, by assuming general subsidence without warping, since it was clearly proved that in addition to the absence of differential warping the position of mean sealevel in New York harbor had not changed, with reference to old benchmarks, in a quarter of a century. The fact that waves are eroding the coast and destroying certain property does not appear to be significant, since the same thing occurs on lakes where there is no change in the relative level of land and water. Waves will continue to erode a shore indefinitely, whether or not the coast subsides.

SOME HISTORICAL EVIDENCE OF COASTAL SUBSIDENCE IN NEW ENGLAND

BY CHARLES A. DAVIS

(Abstract)

During the summer of 1913 the writer found at many points near Boston, Massachusetts, various kinds of evidence that there has been a definite, progressive, and measurable elevation of the high-tide level with regard to the coastline since the settlement of the coastal region by white men.

Taken in connection with the structure of the salt marsh peat beds of the same localities, which are in some places more than 20 feet thick, built up entirely of the remains of plants which grew only at the mean high-tide level, as already reported by the writer, this steady elevation of the high tides can only be interpreted to mean a subsidence of the coast in the region reported on.

Presented in abstract from manuscript.

DISCUSSION

Prof. A. W. GRABAU: Could the examples cited not be explained by settling of the marsh itself and the condensation of the peat, owing to the oxidation of the carbon.

Dr. J. W. SPENCER: On the Island of Saint Eustatius, in the West Indies, foundations of stone buildings (which were constructed before 1781) were observed standing out in the sea. The question arose whether the land has sunken since 1781 or the coast has been washed away, leaving the foundations of commercial structures which had been built below sealevel.

Prof. W. M. DAVIS: The problem of coastal change or coastal stability requires for its satisfactory settlement the consideration of all kinds of evidence. Mr. Davis has just presented a kind of evidence that indicates a slight subsidence in the Boston district; but Professor Johnson has previously presented another kind of evidence—and to my mind stronger evidence—derived from a study of Nantasket Beach at the entrance to Boston harbor, which shows long-continued stability. As long as these two kinds of evidence remain unreconciled the problem can not be regarded as solved, and it is quite as much Mr. Davis's responsibility as any one else's to bring about a proper reconciliation.

In Mr. Davis's references to the depths at which salt marsh deposits have been found, he did not specify their location with respect to the form of shoreline and to the changes that it has suffered in recent centuries. This is of particular importance with respect to the deposits at such depths as 20 feet. In the absence of such specification the bearing of his facts on the solution of the problem can not be properly appreciated by his hearers.

Prof. WILLIAM H. HOBBS: We have had presented evidence of so conflicting a nature that it would seem to be possible to explain them by movements of sections of coast independent of neighboring sections. In studies which I made in Malta during February, 1913, it was found that this island of less than 100 square miles gave a vertical movement in opposite direction and, measured in feet, characterize the eastern and western coasts.

Mr. FRANK LEVERETT: Caution needs to be exercised in analyzing beach phenomena, for conditions differ in some cases that give an advantage for developing high bars that did not obtain at certain other times. Successive beaches also may have the same altitude even if differential uplift or depression is in progress, as is shown by numerous observations on the beaches of the glacial lakes.

Prof. J. W. GOLDTHWAIT: Doctor Davis's evidence will be generally accepted as evidence of *submergence* to a depth less than two feet in historic times. It does not seem to me to be necessarily evidence of *subsidence* of the coast. In view of the great irregularity of the high-tide surface in such harbors as Boston harbor, as Professor Johnson has just shown to occur, and the considerable reduction of the area overflowed at high tide by the reclaiming of land along the water front of the city and its suburbs, would not Dr. Davis say that the submergence of less than two feet may be due to a local raising of the high-tide surface rather than to a downward movement of the land?

Prof. D. W. JOHNSON: Doctor Davis is right in saying that we ought to find some cases of a lowering of the high-tide surface, producing apparent elevation, if the theory of coastal stability with tidal fluctuations be true; and he will find a number of cases of this very phenomenon cited in my published papers on coastal stability. The person who doubted the existence of any historical evidence in favor of subsidence could not have been familiar with the literature, for there is a wealth of published evidence supposed by the authors to prove subsidence within recent historic times—much of this evidence similar to that just presented by Doctor Davis. But it should be noted that the localities mentioned by Doctor Davis are in an area where I have demonstrated a difference of three feet in the elevation of the high-tide surface within short distances—an area subject to strong local fluctuations in tide height. All of the phenomena mentioned by him can be easily explained without invoking recent subsidence—the deep peat deposits being of more ancient date than the beach ridges which prove stability, the shallow deposits of artificial products having reached their present position through settling of the marsh deposits, local changes in tide levels causing upbuilding of marsh surface, etcetera. The theory of coastal stability satisfactorily accounts for all the facts so far advanced—as Prof. W. M. Davis rightly demands of any theory presented for our consideration—if we recognize the possibility of an early subsidence previous to the period now under discussion, and admit the existence of the local tidal fluctuations which are of such common occurrence along the coast. There fluctuations must have been very marked in the region discussed by Doctor Davis because of dredging, the interfering action of numerous piles for trestles, and natural shoreline changes.

Further remarks were made by Dr. J. M. Clarke.

Doctor DAVIS replied to questions and remarks as follows:

To Professor Grabau: The structure and composition of the peat are such that shrinkage and compression to any extent are not possible. The peat below low-tide level is no more compressible than water; that above is practically silt bound together by roots and stems of grasses. The plant remains in the lower beds show no compression, though fragile.

To Doctor Spencer: The structures referred to in the paper were not built below tide level at a distance from the shore and the intervening land cut away, but were erected on the tide water and have simply been buried where they stood.

To Doctor Clarke: Beaver dams have been found in a salt marsh below low-tide level.

To Prof. W. M. Davis: The fact that the Nantasket beaches show apparent stability is offset by the fact that in a series of beaches forming the "Point of Pines" at the north end of Revere Beach the shoreward or older beaches are distinctly lower than the one at the present seaward beach, so much so that the spits or ends of the older beaches are now nearly buried by the salt marsh landward and those of the more recent ones are still well above its level.

To Doctor Goldthwait: The idea of local change in high-tide level because of filling the Back Bay in Boston does not appear tenable, since the decrease in the size of the basin would so decrease the velocity of the water entering the opening that not so much would enter as before the arm was closed, and the elevation of the tide would be inappreciable. This may be confirmed by the condition in the North River, where no filling has been done, yet which shows about the same amount of tidal elevation as in the marshes cited in the paper.

To Professor Johnson: It is not possible that the salt marshes were formed previous to the Nantasket beaches, since if this were true the salt marshes by this time would have ceased to exist as such and have been converted into fresh-water wooded swamps from accretions to their surfaces. The entire character of the flora of salt marshes cut off from the sea by dikes has been changed to the writer's knowledge in a period of less than ten years. The structure of the deposits in existing marshes is so homogeneous that there is no question in the author's mind that the conditions prevailing when the lower beds were formed have been in existence throughout their formation and still persist. The theory of change in the form of tidal surface is not sufficiently elastic to cover all of the cases where historic evidence of subsidence exists, nor are the changes proven to exist sufficiently great to account for the deposits covering some of the objects mentioned in the paper.

PLEISTOCENE MARINE SUBMERGENCE OF THE CONNECTICUT AND HUDSON
VALLEYS

BY HERMAN L. FAIRCHILD

(Abstract)

It has long been known that during the waning of the latest ice-sheet New England stood lower with reference to sealevel than at present, but the full amount of submergence has not been recognized. The terraced plains of the Connecticut Valley have generally been attributed to the river, enormously swollen by the glacial outflow.

In the Massachusetts section of the Valley Professor Emerson recognized the phenomena as due to static waters, and he correctly discriminated the work of the standing water in the open valley from that of the superior glacial streams and lakes, and also from that of the much inferior river flood. His levels for Massachusetts give us a theoretic plane for the sealevel waters. This plane

projected south and north and is found to very closely coincide with the highest shoreline features.

The marine plane in the Connecticut Valley has the same gradient as the marine plane in the Hudson Valley, 2.23 feet per mile, but the altitudes in the former valley are 50 feet higher than those of corresponding latitudes in the Hudson Valley. The isobases lie about 20° north of west by south of east. The uplifted and tilted marine plane has altitudes approximately as follows: Riverhead, Long Island, 120 feet; New Haven, Connecticut, 180; Middletown, 220; Hartford, 260; Springfield, Massachusetts, 300; Brattleboro, Vermont, 420; Hanover, New Hampshire, 565; Wells River, Vermont, 620.

Presented in abstract without notes.

DISCUSSION

Dr. J. W. SPENCER: In confirmation of Professor Goldthwait's statement that the Connecticut terraces rise in steps, it may be stated that I made an investigation of these, as well as the terraces of the Lemville and Sal in 1895 and 1898; but the work has never been published except in a short abstract.¹⁶ These valleys radiate west, east, and south from near the same highlands, yet they all show that the terraces descend by steps and do not conform to the valley slope, which features are not evidence of simple deformation or recent tilting, as assumed by Professor Fairchild.

Prof. W. N. RICE: I wish to call attention to a phenomenon near Middletown, which seems to be evidence of the view held by Woodworth in regard to the terraces of the Hudson estuary and by Gulliver in regard to the terraces of the estuarian portions of the Thames and the Connecticut. Just below Middletown, in Portland, between the high terrace and the river, is a well characterized esker, first observed by Gulliver, whose crest is 30 to 50 feet below the terrace. Apparently the terrace must have been formed while the ice was still present in the valley. The great abundance of boulders up to 2 feet or more in diameter in the irregularly stratified material of the terrace seems to point in the same direction.

Prof. J. W. GOLDTHWAIT: Some of us who have worked recently in the field shown on Professor Fairchild's map feel that in raising the level of the Pleistocene sea from 525 feet at Covey Hill, where he formerly put it, to 750 feet, and from zero at New Haven, where his predecessors had it, to 180 feet, he is getting into deep water. Working toward Covey Hill, Canada, from the south and west, Professor Fairchild has reached the conclusion that the upper limit of marine submergence at that place is at 750 feet. Working toward Covey Hill from the east and north, I have been led to place the marine limit at 525 feet, coinciding with the Gilbert Gulf water plane of Professor Fairchild. Our failure to agree appears to be due in part to differences in observation of facts at Covey Hill, as well as to their interpretation.

In the Connecticut Valley it seems to me the evidence presented by Professor Fairchild is too incomplete to warrant conclusions as to marine submergence. One of Prof. James D. Dana's papers, to which he alluded, presents, however,

¹⁶ Proc. Am. Asso. Adv. Sci., vol. xlv, 1896, pp. 139-140.

in the form of a profile, a large number of measurements of altitude of tributary deltas and other gravel deposits, which are shown to conform not to a single northward-rising plane, but to a steplike series of such planes, alternating with shorter, steeper curves—the whole profile thus suggesting that of an ungraded river or chain of lakes subsequently upwarped.

It seems to me that still greater difficulty awaits Professor Fairchild in the eastern part of Massachusetts, where his isobases if extended, everywhere curved considerably, would seem to require marine submergence of 300 to 400 feet. The evidence near Boston in outwash gravels with kettle holes, within 30 feet of sealevel, seems impossible to reconcile with such deep submergence.

The general session adjourned at 12.30 o'clock p. m.

At 2.30 p. m. the Society met in joint session with the Paleontological Society and listened to the address of Dr. Charles D. Walcott, President of that Society, on "The Cambrian of Western North America."

At the close of this address the Society reconvened in sections as before.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE FIRST SECTION
AND DISCUSSIONS THEREON

The first section convened at 3.48 o'clock p. m., with Vice-President R. D. Salisbury in the chair and E. O. Hovey acting as secretary. The following papers were offered:

CAUSE OF THE POSTGLACIAL DEFORMATION OF THE ONTARIO REGION

BY J. W. SPENCER

(Abstract)

The measured postglacial deformation between the head of Lake Ontario and Parishville (near Potsdam, New York) is 540 feet, and to this must be added 120 feet for the Erie region east of Cleveland. Some have attributed this movement to the removal of the ice-sheet.

The anomalies of terrestrial gravity (Hayford and Bowie) show an excess of terrestrial weight at Potsdam equal to 700 feet of rock, but at the northern end of Lake Champlain, where the glaciers were thick, there is now only an excess of 35 feet, while at Albany there is a deficiency of 1,435 feet, at Ithaca 765 feet, and at Cleveland 100 feet (all in glacial areas). The deformation below the outlet of lake is seen to be connected with the earth movements quite independent of the ice-sheet; the earth movements seem to be related to the Laurentian mass and almost independent of the Adirondack outlier.¹⁷

Presented in abstract without notes.

¹⁷ Am. Jour. Sci., vol. xxxv, pp. 261-273.

DISCUSSION

Prof. A. P. COLEMAN: One can not expect exact accordance between the ice-lobes and areas of elevation. In general the ice-covered regions have risen—for example, America, Patagonia, and northeastern Europe.

Doctor SPENCER replied as follows: It is significant that their observations, indicating the recent measured deformation of the land as being independent of the retreat of the ice-sheet, is in conformity with the relationship between the anomalies of gravity and the earth movements—investigations by entirely different methods. The great earth movements are not as extensive as hinted by the ice-sheet. The ice-covered areas show subsidence and also deformation. The mere occurrence of deformation in lately ice-covered areas is no proof of the tilting being due to the removal of the glacier. Deformation occurs in the Appalachian belt south of the ice-sheet, which could not have affected it.

Further remarks were made by Mr. F. B. Taylor.

ORIGIN OF DOLOMITE

BY FRANCIS M. VAN TUYL¹⁸

(Abstract)

The theories of the origin of dolomite and the experimental evidence of its formation were briefly discussed. Recent studies of the dolomites of the Upper Mississippi Valley for the Iowa Geological Survey, supplemented by independent observations on the dolomitic formations of the Appalachian region, have furnished evidence that the great majority of dolomites have probably resulted from the secondary alteration of limestone. In most cases the alteration certainly took place beneath the sea.

Presented by title in the absence of the author.

FLATTENING OF LIMESTONE GRAVEL BOULDERS BY SOLUTION¹⁹

BY JOHAN AUGUST UDDEN

(Presented by title before the Society, December 31, 1913)

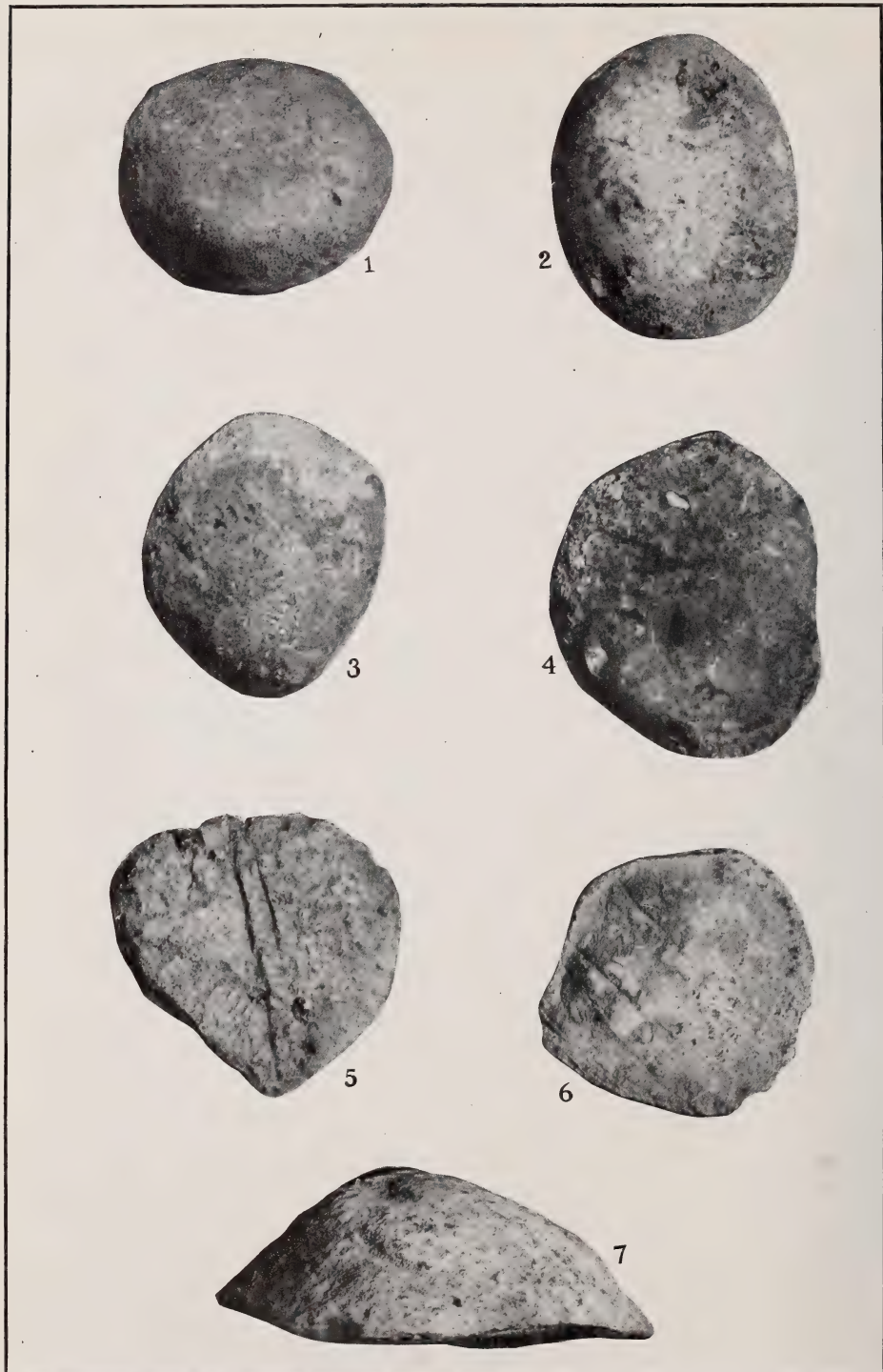
<i>Contents</i>	<i>Page</i>
General statement.....	66
Origin of the gravels.....	67
Description of different kinds of flattening.....	67
Conclusions.....	67

GENERAL STATEMENT

Some gravels occurring in the lower valley of the Rio Grande River in Texas consist of white limestone derived from the Comanchean, and also in part from the Pennsylvanian, found in the westernmost part of the State.

¹⁸ Introduced by James F. Kemp.

¹⁹ Manuscript received by the Secretary November 19, 1913.



LIMESTONE BOULDERS

These seven boulders (slightly reduced) were flattened and etched by the solvent action of meteoric water. Number 1 is very slightly affected. Numbers 2, 3, 4, 5, and 6 are arranged to exhibit successive stages of flattening. Number 6 is nowhere more than three-sixteenths of an inch in thickness. A transverse radial section of the upper right-hand margin of this specimen would show a slightly cuspidate extension. This and number 5 both have etched furrows following straight joint planes. Number 7 is a part of a boulder, from which more than one-half has been etched away on one side, while the segment in the photograph, shown edgewise, was preserved almost intact because it was securely lodged in a protecting matrix.

The gravels referred to are of Pleistocene age and are remnants of terraces now undergoing destruction by weathering and erosion.

ORIGIN OF THE GRAVELS

Gravel of the same kind is now in the process of making in the wide channels of several of those tributaries to the river which drain the Edwards plateau. Las Moras and Tequesquite creeks when flooded roll streams several hundred feet wide of such bouldery gravel. The average size of the boulders, or pebbles, is perhaps 2 inches in diameter. The limestone from which these boulders are worn is usually thick bedded and lacks for the most part marked laminated structure. The texture of the limestone is superficially somewhat uniform in all directions. Cleavage is about as easy in one direction as in another. The result is that the pebbles and boulders of this stream gravel are spheroidal in form. They wear round. A certain small per cent of pebbles of flattened form can indeed also be found. This consists of limestone, with well defined laminated structure and consequent parallel planes of easy cleavage.

There can be no doubt that the remnants of terraces referred to were built up from similar gravels transported into the Rio Grande and rolled by this river in the same manner. On the American side of the river the gravels are most abundant for a distance of 20 miles below where the river leaves the Edwards plateau, between Del Rio and Eagle Pass.

DESCRIPTION OF DIFFERENT KINDS OF FLATTENING

On the upper level tracts of these terraces and on their dissected slopes it is often difficult to find a pebble or boulder of limestone that is spherical. All are flattened, oblate spheroids. Looking at their shapes more closely, we find now and then a pebble in which the longest diameters all around mark a sharpened edge. It is evident that such edges never were worn to their present shape by trituration in a gravel stream. Some pebbles are hemispherical in form, having one side more flat than the other. On the pebbles of most pronouncedly flattened form one frequently finds shallow concavities on the surface, showing the result of etching by solution. In very rare cases one may see etched grooves radiating from the elevated center of one of the flattened surfaces of these boulders. This radiated, furrowed sculpture is one of the most common sculpture forms seen on the bare limestone surfaces *in situ* in this part of America.

CONCLUSIONS

It is quite evident that the flattening of these small boulders is caused by the solvent action of the rain water. It is often greatest on the exposed upper surface of each boulder. But the process is clearly so slow that most of the boulders have had time to be turned over, perhaps many times, by the creeping of the upper surfaces of the terrace and by other superficial accidents due to the wind, to plants and to animals tramping and burrowing into the ground. With the smallest beginning of flattening there will always be a tendency of a boulder to lodge whenever disturbed, with its equatorial plane in a horizontal position. The hemispherical boulders were probably subjected to prolonged planation in one undisturbed position. The ultimate result of the

process of solution is complete destruction. The penultimate condition is that of a thin chip of limestone, in which the original circular form of the equatorial plane is not always evident. This may be due altogether to the process of solution, or it may also be caused by fracturing of the rock fragment, as it becomes very much thinned by surface etching.

The process is, of course, limited to the surficial part of the gravel deposits. Gravels of this kind can have but a very limited occurrence in older formations, since they can be formed only in deposits in the process of destruction.

Presented by title in the absence of the author.

HIGH-LEVEL LOOP CHANNEL

BY T. C. HOPKINS

(Abstract)

The channel has an east-west direction across the north-south ridge between Butternut Valley on the east and Onondaga Valley on the west. The floor of the valley is more than 50 feet above the Butternut Valley and more than 200 feet above the Onondaga Valley. The channel is 150 to 250 feet deep in the ridge. Near the middle of this channel is a loop on the south side nearly two miles long around a large hill. The east end of the loop meets the direct channel at grade, but at the west end of the loop the bottom of the loop part of the channel varies from 20 to 65 feet above the nearly level floor of the direct channel.

Presented by title in the absence of the author.

DIVERGENT ICE-FLOW ON THE PLATEAU NORTHEAST OF THE CATSKILL MOUNTAINS AS REVEALED BY ICE-MOLDED TOPOGRAPHY

BY JOHN L. RICH²⁰

The contour maps of the northeastern angle of the plateau of central New York, lying between the Hudson on the east, the Mohawk on the north, and the higher Catskills on the south and southwest, bring out a striking topography characterized by smoothly flowing and spreading lines diverging from a point just off the edge of the plateau and about 6 miles southwest of Schenectady.

A reconnaissance examination of the region shows that two features, both the result of glacial action, are responsible for this topography. Of these a finely developed and extensive group of drumlins is the most important. Of less importance than the drumlins, but still contributing noticeably to the flowing outlines, bedrock fluted by ice erosion constitutes the second feature. From the point of divergence the drumlins extend in spreading lines westward at least to Schöharie Creek and, if one may judge from the contour maps, some 15 or 20 miles farther across the Fonda Quadrangle; southwestward about 10 miles to Fox Creek, and southward at least to the base of the Catskills near Cairo, a distance of about 35 miles (figure 1).

²⁰ Manuscript received by the Secretary January 2, 1914.

The route followed in the reconnaissance lay from Gallupville (Berne Quadrangle, New York) east and northeast to the neighborhood of Thompsons Lake and the Helderberg scarp at Indian Ladder, thence south past Wolf Hill, Troutner Lake, Westerlo, Medusa (Durham Quadrangle), and Oak Hill to East Windham.

The east-west set of drumlins is best developed about 3 miles northeast of Gallupville, where the long, smooth ridges and boat-shaped troughs give a

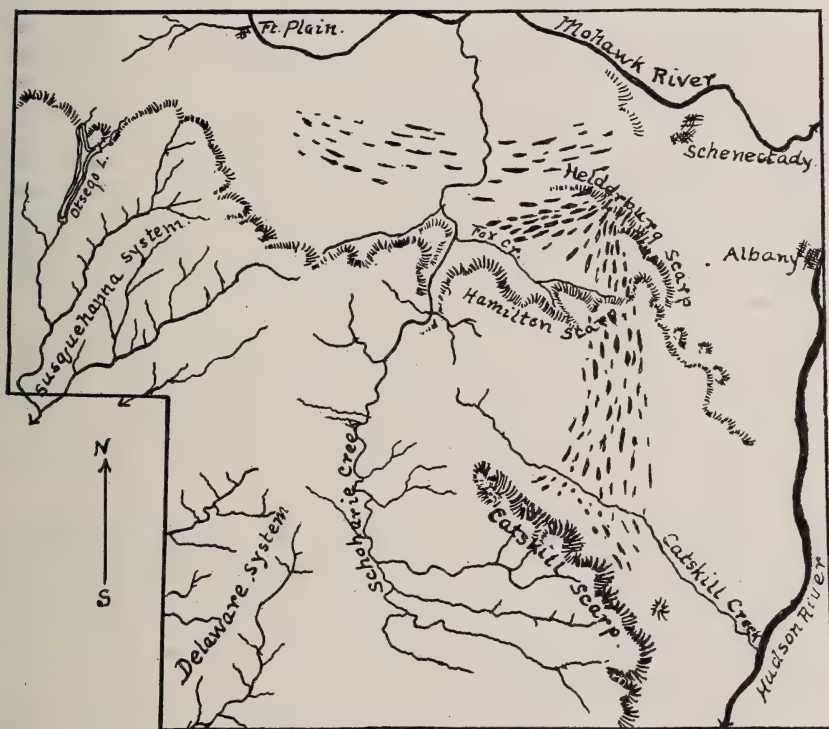


FIGURE 1.—Sketch Map of a Portion of eastern central New York

The map shows the dominant elements of the physiography and the location of the drumlin belt here described. The drumlin symbols indicate merely the general distribution and the prevailing directions of the drumlins, not individual drumlins. Drumlins west of Schoharie Creek have not been seen by the writer. They are inserted here on the evidence of the topographic map. This belt of drumlins doubtless continues westward and joins with that north of Otsego Lake.

typical washboard topography. Many of these drumlins are over 2 miles in length, but all are narrow. All exposures in roads and in wells show bouldery till, in which limestone fragments are exceedingly abundant. These drumlins are not confined to the surface of the plateau; they occur also on the slope rising to the plateau from the east, especially near East Township.

So far as could be determined in a reconnaissance trip, all these drumlins seem to be composed of drift. No rock-drumlins or drumlin-like forms carved out of rock were noted.

The belt of north-south drumlins extending southward from Thompsons Lake to the Catskills is separated into two parts by a pronounced escarpment, developed on Hamilton rocks, which runs eastward along the south side of the valley of Fox Creek from Schoharie to Countryman Hill. This escarpment opposed a considerable topographic barrier to the ice movement, and in turn suffered severe glacial erosion, as is evidenced by the strong rock fluting which it now displays. The lower north-south passes through the escarpment suffered most. Harder ledges resisted erosion, while the overlying softer shales were stripped away until the hillsides were carved into a series of steplike terraces, smooth and straight and inclining southward with the dip of the rocks, each terrace marking the outcrop of a resistant rock layer. One valley in particular along our route—about $2\frac{1}{2}$ miles southeast of East Berne—shows this feature especially clearly. The valley, which constitutes a pass through the escarpment, is U-shaped and about three-fourths of a mile wide at the bottom. The valley bottom in its northern part, near the edge of the escarpment, is rock only thinly veneered with drift, while the sides are beautifully fluted. A little over half a mile to the south a large, complex drumlin mass rears itself to a height nearly as great as that of the rocky and fluted valley walls on either side—an interesting juxtaposition of erosional and constructional glacial features. From here south to Catskill Creek the drumlins dominate the landscape, becoming broader, shorter, and more variable in direction as one goes farther south, until near Catskill Creek some of them are nearly round.

South of Catskill Creek a number of rounded hills, in which no rock exposures could be found, appear to be drumlins. Here the drumlins seem to exhibit a strange indecision as to which direction to take, but show on the whole a tendency to diverge along two lines, one running southwest toward the pass south of Mount Pisgah and the other southeast along the eastern front of the Catskills—probably in response to divergent ice-currents occasioned by the Catskill escarpment.

Throughout the area described above there seems to be surprisingly little true moraine. A few masses, one just west of Reidsville and another a mile south of Medusa, were noted, but on the whole drumlins constitute the dominant glacial features.

The region as a whole presents a beautiful example of ice-molded topography of both the constructional and the destructional types and records in the clearest manner the splitting of the ice-currents against the northeastern angle of the plateau into a south-flowing stream in the Hudson Valley and a westward-flowing stream in the valley of the Mohawk.²¹

Presented by title in the absence of the author.

²¹ After this paper had gone to the publishers the writer discovered, under the heading "Work in Progress," in the report of the Director of the New York State Museum (Bulletin No. 149, page 18), a notice to the effect that Prof. A. P. Brigham had visited a part of the region here described, had noted the diverging drumlinoid forms, and had put on them the interpretation of diverging ice flow in the Hudson and Mohawk Valleys. Professor Brigham's results are not as yet published. The observations and interpretations here presented may therefore be looked upon as independent confirmation of Professor Brigham's interpretation.

LENGTH AND CHARACTER OF THE EARLIEST INTERGLACIAL BEDS

BY A. P. COLEMAN

(Abstract)

The earliest interglacial beds at Toronto correspond in age to deposits in New York and on both sides of Lake Erie. They are almost certainly of the same age as lignites, occurring at 27 points on the Hudson Bay slope, 400 miles north of Toronto. They are probably equivalent to the Aftonian interglacial beds, since the fossils, so far as they can be compared, are of the same genera and perhaps of the same species. It is probable that the mammals of the Toronto formation are all extinct; 70 out of 72 beetles are extinct and several of the trees. The thawing of the Labrador ice-sheet is proved to have extended to within 300 miles of the glacial center, and the warmth of the climate was greater than now; so that the ice must have entirely disappeared at this period. Interglacial sections at Toronto disclose valleys deeply carved by rivers before the beds were laid down and also after they had been completed. The time necessary to carve these valleys and to deposit 185 feet of delta materials must have been thrice as long as post-Glacial time, say 75,000 to 100,000 years.

Presented in full without notes.

AGE OF THE GLACIAL DEPOSITS IN THE DON VALLEY, TORONTO, ONTARIO

BY G. FREDERICK WRIGHT

(Abstract)

Current estimates of the age of the Don glacial deposits are clearly in conflict with the evidence of a more recent retreat of the ice from the southern watershed of Lake Erie, where abundant facts show that the southern shoreline of Lake Warren can not be more than 12,000 or 15,000 years old; but this is, of course, considerably older than the latest glacial deposits in the Don Valley. Facts have been collected to show that the glacial lakes, on whose shores the lake ridges south of Lake Erie were formed, continued only about 1,000 years, while the sedimentary deposits of the terrace exposed at Scarboro appear to have been accumulated in about 3,000 years, which would represent the time that elapsed after the opening of drainage south of the glacial ice in the Mohawk Valley and the final opening through the Saint Lawrence. The miniature Niagara gorge southwest of Syracuse probably represents the work done in this line of drainage during the accumulation of the fluvial glacial deposits in the Don Valley.

There is much convincing evidence that the first glacial advance over this area proceeded from the Keewatin center, which, after a partial retreat, gave place to the ice from Labrador. It is possible, and indeed probable, therefore, that the southern species of plants and animals found above the lower glacial deposits in the Don Valley and incorporated in the later fluvial deposits are specimens of the earlier deposits which were disturbed by the latter and re-deposited, as it is now generally believed that the sea-shells on Moel Tryfaen, in Wales, and Macclesfield, England, were deposited.

Presented in full without notes.

DISCUSSION OF PRECEDING TWO PAPERS

Prof. H. L. FAIRCHILD: Estimates for the life of Lake Ontario make it not less than 10,000 years. Before Ontario came into existence the basin was covered by waters confluent with the sea. The uplift at the head of the Saint Lawrence has not been less than 154 feet. With the slow movement altogether probable for diastrophic movement, it seems likely that the marine interval was fully as long as the life of Ontario. Before the marine episode the glacial Lake Iroquois accomplished an effect comparable to that of Ontario. That gives a total of 30,000 years for the simplest history that is possible since the inception of Iroquois. Of course this is a crude estimate and the years may be vastly more.

Prof. FRANK CARNEY: Concerning Professor Wright's reference to the age of Plum Creek, stream erosion in a given time interval varies with several factors. Even if it could be shown that the precipitation factor involved no cycles in the lapse of several thousand years, it is certain that a tributary stream can not cut a channel below that of its major. The resistant Berea sandstone in the vicinity of Elyria, Ohio, forms a local baselevel in the West Branch of Block River, to which Plum Creek is tributary. Plum Creek can not cut its channel below that of the West Branch at the junction point; hence the comparatively slight amount of erosion accomplished by Plum Creek since the extinction of Lake Maumee. The amount of erosion done in a certain segment of a valley in a particular length of time is an unreliable unit with which to estimate the time required for the making of the valley.

Mr. FRANK LEVERETT called attention to evidence from northern Minnesota that the Keewatin and Labrador centers of glaciation were each extensive at the same time. This disposes of the suggestion of alternating glaciation in these two centers made by Tyrrell in reference to the Wisconsin glaciation. Evidence is not so clear in reference to earlier stages.

Prof. R. D. SALISBURY called attention to the fact that the rate of erosion has been greatly increased since cultivation of the soil has begun. Based on present rates of erosion, estimates of time necessary for the total of post-glacial erosion are likely to give much too small results.

Prof. N. H. WINCHELL called attention to the non-application of the discussion of the length of post-Wisconsin time to the question of the age of the Don Valley leaves and of the Scarboro section, since they are much older. The age either of the Plum Creek gorge or of the lakes that followed the Wisconsin ice-epoch are only late episodes of a greater drama which began at an earlier date. In the earlier portion of the great period, according to Professor Coleman's photographs and his explanation, there were accumulated four boulder clays indicating four ice-epochs prior to the Wisconsin epoch. These boulder clays seem to be chronologically about parallel with four ice-epochs which have been determined in the western country occurring since the Kansas epoch, namely, Iowan, Illinois, etcetera, this being the most eastern point, apparently, at which these minor epochs have been detected by the existence of actual boulder-clays earlier than the Wisconsin epoch. It is probable that other traces of these earlier ice-sheets will be discovered as time passes.

Prof. G. F. WRIGHT: I have no occasion to differ from Professor Fairchild when he gives to Lake Ontario in its present dimensions an age of about 7,000 years, but I fail to see the evidence on which he would extend indefinitely the time occupied in the retreat of the ice so as to open the line of drainage for Lake Iroquois through the Mohawk Valley and later through the Saint Lawrence, and also that required for the elevation of the beach lines culminating in the Saint Lawrence Valley and farther north. On the contrary, there is abundant evidence that these movements went on with great relative rapidity at the close of the Glacial period.

With regard to Professor Coleman's statement that the rocky fragments in the lowest till in the Don River Valley show that they have been transported in the direction of the Labrador movement, I can only say that the evidence is somewhat indeterminate, owing, first, to the fact that it is merely negative evidence, since the limestone rocks transported may be found to have existed farther west than he supposes; or, again, that through early fluvial transportation fragments may have been carried in a westerly direction some distance from their original position. But admitting that the deposits are all the result of the Labrador movement, there is still the same doubt respecting them which we have already expressed with regard to the supposition that the remains of warm species found in the interglacial deposits are of individuals that actually lived there in interglacial time. I must again emphasize the fact that the shells at Moel Tryfaen and Macclesfield are not all fragmentary and are not contained in till, but in fluvial and lacustrine beds connected with the melting of the glacier.

Further remarks were made by Mr. F. B. Taylor, and brief replies were given by the two authors.

The section adjourned at 4.45 o'clock p. m.

The second section, having finished on Tuesday the papers on its program, merged on Wednesday with the meeting of the Paleontological Society.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE THIRD SECTION
AND DISCUSSIONS THEREON

The third section met at 3.30 o'clock, with Vice-President James F. Kemp in the chair and Frank R. Van Horn serving as secretary.

MANGANESE DEPOSITS OF CONCEPTION AND TRINITY BAYS, NEWFOUNDLAND

BY NELSON C. DALE²²

(Abstract)

At various places in Conception and Trinity bays of Newfoundland manganese is found as a marine deposit interbedded with Lower Cambrian shales

²² Introduced by Gilbert van Ingen.

and limestones. These deposits occur at Manuels, Topsail, Long Pond, Chapel Cove, and Brigus, within 10 miles of each other, on Conception Bay, and are also found some 50 miles to the northwest, on Smith Sound, in Trinity Bay, and are said to occur as well some 50 miles to the southwest, on Placentia Bay. They are best seen and studied in Manuels Brook, where the deposit occupies an interrupted zone of some 20 to 30 feet, consisting of an alternate series of rhythmic bands and lenticles of green, brown, and red color of jaspery aspect, and nodules of pink and green color, and other bands of crystalline character, the whole series interbedded with red and green shales. On analysis the jaspery bands and nodules are found to be complex manganiferous carbonates. They are of undoubted primary marine origin because of their sedimentary association, such as their occurrence in conformable beds at the same horizon at widely separated points and containing fossils in the beds adjacent to the nodular bands within the manganiferous zone.

Read in full from manuscript.

GEOLOGY OF THE WABANA IRON ORE OF NEWFOUNDLAND

BY ALBERT O. HAYES ²³

(Abstract).

The paper describes the petrology, chemistry, and origin of extensive primary bedded deposits of oolitic iron ore which occur on Great Bell Island, Conception Bay, Newfoundland, in sediments of Arenic age, and yield annually more than 1,500,000 tons of ore for export to Canada, the United States, England, and Germany. A distinctive fauna exhibiting European affinities is preserved in the ore horizon. The oolitic iron ore of the Armorica Peninsula, France, holds a similar fauna and is almost identical lithologically. The results of an exhaustive investigation into the petrology and chemistry of the ore are followed by a discussion of its origin. The iron-bearing minerals are shown to be hematite, green silicates similar to thuringite and chamosite, and siderite. Photographs and descriptions of thin-sections, accompanied by chemical analyses, illustrate the character of the ore. The presence of from 1 to 2 per cent of phosphorus in the ore is shown to be due to fossil brachiopods composed largely of calcium phosphate. The stratigraphy and paleontology of the ore series support the view of their primary bedded origin and indicate that they were laid down in bays as marine off-shore shallow-water deposits. Certain kinds of marine life, such as brachiopods, trilobites, and worms, lived abundantly in these waters and indicate that excessive concentration of iron salts could not have occurred, while the presence of algæ in the ferruginous beds suggests the iron-fixing action of such organisms as the means of concentration.

Read in full from manuscript.

²³ Introduced by Gilbert van Ingen.

*GEOLOGY OF THE CUMBERLAND-DIAMOND HILL DISTRICT, MASSACHUSETTS-
RHODE ISLAND*

BY CHARLES H. WARREN AND SIDNEY POWERS

(Abstract)

The Cumberland Diamond Hill district is well known from the occurrence of cumberlandite on Iron Mine Hill. The other most striking geological features are a stock of riebeckite-aegirite granite and a large mass of vein quartz forming Diamond Hill. The alkaline granite is closely allied to the Quincy-Blue Hills riebeckite granite and to a small stock near Sharon, south of the Blue Hills.

Evidences of four periods of igneous activity are found in the region. The earliest is pre-Cambrian, but later than the deposition of the green schists and quartzites in the Blackstone River Valley. Gabbro, cumberlandite, and labradorite porphyry dikes were intruded. The second period is Lower Paleozoic. All the biotite granites of this region are thus dated from the evidence found near North Attleboro, where the granite is thought to cut Cambrian sediments. The third period is Devonian (?), at which time the alkaline granites were intruded. These granites cut the biotite granites, and pebbles of them are found in the Norfolk Basin sediments of Pottsville age. The last period is Pennsylvanian, when dacitic lavas were extruded at Diamond Hill. At the close of the Carboniferous the dacites were faulted and brecciated. Up the fissures so formed came hot siliceous waters, replacing the dacite and forming the mass of quartz at Diamond Hill.

Presented by Mr. Powers in abstract without notes.

*SEDIMENTARY CHARACTER OF GARNETIFEROUS HORNBLENDE SCHIST,
HANOVER, NEW HAMPSHIRE*

BY JOHN WESLEY MERRITT²⁴

(Abstract)

A garnetiferous hornblende schist found at Hanover, Grafton County, New Hampshire, has been described in Bulletin 150, United States Geological Survey, and tentatively classed among schists and gneisses of igneous origin. Field and petrographic study of this rock and its associates furnish many evidences of sedimentary origin.

Read in full from manuscript.

OOLITES OF THE CHIMNEYHILL FORMATION, OKLAHOMA

BY CHESTER A. REEDS²⁵

(Abstract)

The oolites of the Chimneyhill formation are for the most part calcareous. In the upper portion of the bed, however, bands, stringers, and lentils of chert

²⁴ Introduced by J. W. Goldthwait.

²⁵ Introduced by E. O. Hovey.

are not uncommon. The thickness, the dip, the strike, and the content of the oolitic stratum is variable throughout the 106 miles of its linear extent. The microscopic examination shows, in some cases, oolites of a uniform size, while in others they are in all stages of development. A few oolites possess primary nuclei, many none at all, the remainder having secondary nuclei. In the cherty areas the calcareous oolites have been wholly or partially replaced by silica.

Presented in abstract without notes.

DISCUSSION

Dr. GEORGE P. MERRILL asked whether the calcite in the oolites might not be recrystallized in place and not have been introduced in a secondary manner.

Doctor REEDS replied that he considered it quite probable.

Prof. O. C. FARRINGTON asked whether oolites are of organic or inorganic origin.

Doctor REEDS answered that he considered them of inorganic origin.

TEMISKAMITE, A NEW NICKEL ARSENIDE FROM ONTARIO

BY T. L. WALKER

(Abstract)

This mineral occurs in calcite veins carrying niccolite and native bismuth. Temiskamite resembles niccolite, but is pale lilac in color. No crystallized material has been observed, the mineral being radiating fibrous in botryoidal forms.

Luster metallic; specific gravity, 7.901; hardness, 5.5; fusibility, 2. Freshly broken surfaces readily tarnish to colors resembling bornite.

A chemical analysis shows the following result:

Nickel	49.07 per cent $\div$ 58.7	= .8359	} .8652
Cobalt	1.73 per cent $\div$ 59	= .0293	
Arsenic	46.34 per cent $\div$ 75	= .6179	} .6500
Sulphur	1.03 per cent $\div$ 32	= .0321	
Bismuth	.55 per cent		

Total..... 98.72 per cent

Formula $(\text{Ni. Co})_4 (\text{As. S})_3$ —or $\text{Ni}_4 \text{As}_3$.

Bismuth content is thought to result from inclusion of native bismuth.

Presented in abstract without notes.

OOLITIC AND PISOLITIC BARITE FROM THE SARATOGA OIL FIELD, TEXAS

BY E. S. MOORE²⁶*(Read before the Society December 31, 1913)**Contents*

	Page
Introduction.....	77
The physical characters of the concretions.....	77
Chemical composition and origin of the concretions.....	79

INTRODUCTION

While drilling in the Saratoga oil field of Texas the geologists of the Rio Bravo Oil Company recently found some peculiar concretions. Through the kindness of Messrs. E. T. Dumble, the vice-president and chief geologist of the company, and C. L. Baker, who respectively granted permission to publish an account of them and sent material for investigation, the writer has been able to present the following report on these structures, and has concluded that it is the first time this particular type of concretion has been described.

The concretions came from two localities—Batson and Saratoga—the former about eight miles west of the latter and at practically the same surface elevation. The wells from which they were obtained are of nearly the same depth, varying from 1,120 to 1,350 feet, and in one case at least they were found in wells in both areas at 1,350 feet. The formations pierced by the wells are reported to be heavy sands, then limy shales, which are followed by gumbo, and this in turn by loose, fine, dark-colored sands, containing oil at a temperature of 125° Fahrenheit. The heavy sands locally carry large concretions of sandstone from 2 to 12 feet in diameter, and the lower side of the sand bed, as well as that of the concretions, is frequently mammillated, the mammillæ often being translucent. Associated with the oil are waters carrying some sulphuric acid, and the concretions occur with the oil in the fine sand. The strata of the area are of Miocene or Pliocene age.

THE PHYSICAL CHARACTERS OF THE CONCRETIONS

The concretions take several different forms. Some of those from a well 1,350 feet deep, at Saratoga, are pisolitic, as they consist of concentric spheres and are from 3 to 5 millimeters in diameter. They are of a dirty-white color. Other samples show irregular structures and the material is porous, somewhat like very fine textured pumice in appearance, and this type was found in wells in both areas. In some cases the structures take the form of rings and resemble travertine, which has been deposited around stems or roots of trees.

The most interesting type, however, came from a well at Saratoga at a depth of 1,130 feet. These are large oolites ranging in size from 1.25 to 3 millimeters in diameter and varying in shape from nearly perfect concentric spheres to ovoids. In thin-section they usually show a great number of extremely fine lines marking the outlines of the spheres. The mineral is cryptocrystalline to amorphous and somewhat opalescent in appearance.

In the center of the oolite there is generally an area of irregular shape occupied by material which is more porous than that surrounding it and it is

²⁶ Manuscript received by the Secretary December 31, 1913.

not concentrically arranged. It consists of an earthy mass, sometimes slightly stained with iron oxide, with extremely small crystals of what seems to be barite arranged along open spaces and mixed with the earthy material. It is possible that some of these crystals are barium-orthoclase, as the optical properties would correspond to those of that mineral. The interference colors are bluish gray and the extinction angle is zero or very small. A little calcite was found in two thin-sections and a little quartz in another, while it is believed that a small amount of clay is also present. In four thin-sections examined and in the large number of concretions crushed for purposes of analysis no definite body, such as a sand grain or similar structure, was found serving as a nucleus. Outside of the earthy, central mass the material is concentrically

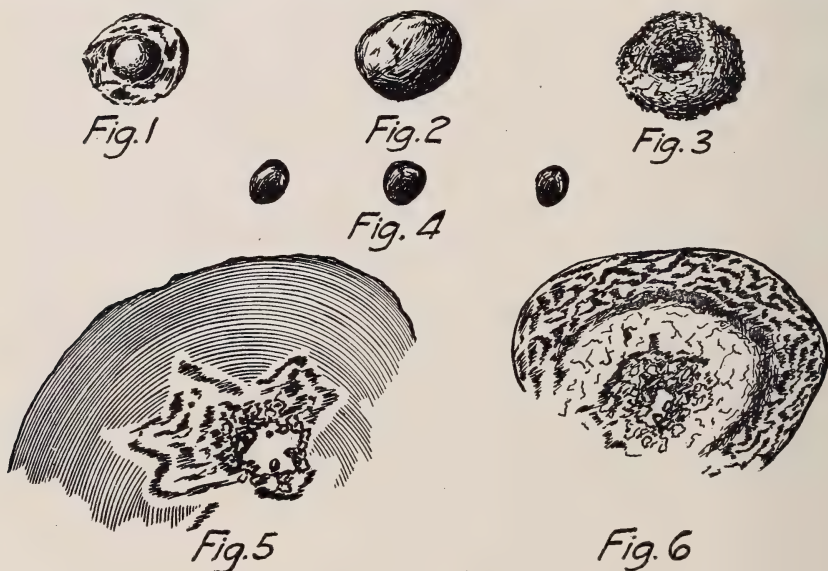


FIGURE 1.—Thin-sections of oolitic and pisolitic Barite

Figures 1 and 2. Pisolitic barite (3 diameters). Figure 3. Barite ring resembling travertine (3 diameters). Figure 4. Large oolites (2 diameters). Figure 5. Thin-section of oolite, showing central structure and fine lines (25 diameters). Figure 6. Thin-section of oolite without well marked concentric spheres.

arranged and the spheres marked by very fine lines. It appears that the concretions began to form by deposition of barite in both a crystalline and earthy condition, with small amounts of other minerals, and that this later continued to precipitate more rapidly in a purer condition, either as a replacement of some other mineral or in open spaces in the sand. No evidence of replacement is found unless it be the traces of calcite existing in some oolites, as the concretions are loose and not embedded in a solid rock.

In color the oolites are white to bluish gray, and they are very smooth on the outer surface. From their appearance they were at first thought to be chert concretions, but an examination showed a specific gravity of 4.25 and a flame coloration for barium, strontium, and a trace of potassium.

This seems to be a new occurrence for barite. It has been reported as occurring in veins, as filling in the interstices of brecciated limestone, quartzite, sandstone, and chert, as nodules and irregular masses in residual clay, in geodes associated with drusy quartz, and always described as crystalline. J. P. Rowe²⁷ describes a deposit of nodular barite and selenite from Montana in which the barite is nodular, radiated, and fibrous. The shape of the nodules is spheroidal and the size of the bodies varies from 5 to 10 centimeters in diameter and 3 to 7 centimeters in thickness. The mineral is whitish blue in color and has a specific gravity of 4.7.

The Saratoga barite somewhat resembles that from Montana in color and form, but it is distinctly oolitic or pisolitic, and it is partly cryptocrystalline to amorphous.

CHEMICAL COMPOSITION AND ORIGIN OF THE CONCRETIONS

As stated above, the flame test indicated barium, strontium, and a trace of potassium. A chemical analysis made by Mr. L. J. Youngs, of the Department of Geology and Mineralogy of the Pennsylvania State College, to whom I am indebted for these figures, showed the following percentages:

SiO ₂	0.98	SO ₃	35.104
Al ₂ O ₃	0.41	H ₂ O	} 0.55
Fe ₂ O ₃	0.07	Vol. matter.....	
CaO	2.129	BaSO ₄	88.54
SrO	2.067	SrSO ₄	3.76
BaO	58.17	CaSO ₄	5.17

From this analysis it is seen that the oolites consist chiefly of barite, with small amounts of gypsum and celestite. Since they are associated with warm water and oil, and since the sandstones are mammillated on the lower side, it seems probable that the barium was carried upward in solution and precipitated by coming in contact with the sulphuric acid waters, which are associated with the oil. The barium may have been carried as a bicarbonate or in a dilute solution of a carbonated alkali. Bischof states that barite is practically decomposed by a dilute solution of a carbonated alkali at a temperature of 77° to 82° Fahrenheit, and at 212° only 1,000 parts of water are required to dissolve barium silicate. W. P. Headden describes the Doughty Springs of Colorado, in which Na, Cl, and CO₂ are abundant, the latter both as free gas and as bicarbonates, and in which barite sinter is being deposited in large quantity.²⁸ Whether the barium in Texas be carried as a bicarbonate of barium, as barium sulphate dissolved in a carbonated alkali, or as a barium silicate, it would readily be thrown down by the sulphuric acid present, as the acid would set free alkali sulphates, which might remain in solution, and precipitate the barium as sulphate.

Read in full from manuscript.

The section adjourned.

²⁷ American Geologist, vol. 33, 1904, pp. 198-199.

²⁸ Am. Jour. Sci., 4th ser., vol. 19, pp. 297-309.

ANNUAL DINNER

The annual dinner of the Society was held in Proctor Memorial Hall, about two hundred persons participating. Frank D. Adams acted as toastmaster, and the speakers of the evening were Eugene A. Smith, George F. Becker, John M. Clarke, J. Stanley-Brown, N. H. Winchell, James F. Kemp, and G. O. Smith.

SESSION OF THURSDAY, JANUARY 1

At 9.30 o'clock a. m. a public lecture was given in Palmer Hall by Arthur L. Day on "Some Observations of the Volcano Kilauea in Action," presenting the main facts of his revised paper as published in volume 24 of the Bulletin, with additional matter.

SOME OBSERVATIONS OF THE VOLCANO KILAUEA IN ACTION

BY ARTHUR L. DAY

(Abstract)

This paper is chiefly concerned with the identification of and the reactions between the gaseous ingredients set free by the liquid lava at Kilauea during the summer of 1912. A successful attempt was made to collect these gases directly from the liquid lava at a temperature of about 1,000° before they reached the atmosphere. The collection of the gas before it has become altered by combustion with air has proved an insurmountable difficulty hitherto, whether the gases were collected in tubes for analysis in the laboratory or whether they were studied at the point of emergence with the spectroscope. In either case the gases were burned or were in process of combustion, and therefore could not reveal either the true identity or the original relation of the gases participating in volcanic activity below the surface.

In so far as the present reconnaissance yields final results, it shows that the gases evolved from the hot lava at the Halemaumau crater are H_2O , CO_2 , CO , SO_2 , free H and free S, with Cl, F, N_2 , and perhaps NH_3 in comparatively insignificant quantity. No argon was found or any of the other rare gases.

The chief conclusion, on finding this group of gases in association at 1,000° or higher, is that they can not be in equilibrium at that temperature and must be in process of active reaction among themselves. There can be no equilibrium, for example, between free sulphur and SO_2 (and possibly SO_3 , since water was also present), nor between free hydrogen and SO_2 or CO_2 .

This is a conclusion of rather far-reaching consequence, for it must mean that the relative proportions of the gases are constantly in process of local change—a fact which is supported by the very considerable differences between the analyses of the gases contained in different tubes which were filled at the same time. Since these reactions are strongly exothermic, it also follows that a very large and constantly increasing amount of heat is set free during the

rise of the gases to the surface. In support of this, it was also observed that when the quantity of gas set free was large the temperature of the liquid lava in the basin was higher (July 6, 1912, $1,185^{\circ}$); when the amount of discharged gas was small it was lower (June 13, 1912, $1,070^{\circ}$), the quantity of lava in the basin remaining substantially the same.

Controverting a view recently put forth, H_2O was found to be present as such among the gases set free, as indeed it inevitably must be, for it has long been known that free hydrogen in association with SO_2 and CO_2 will react to form water at these temperatures.

Neither hydrocarbons nor chlorine in appreciable quantities was found.

The absence of argon is definite evidence that none of the gases composing the volcanic emanation are of meteoric origin.

The paper is somewhat preliminary in character, and will be followed by more detailed studies of the relation of the gases to each other and to the lava at the temperatures which prevailed in the volcanic vent.

After Doctor Day's lecture, the Society repaired to Guyot Hall, where the general session was called to order, with President Eugene A. Smith in the chair.

By vote, the Council report was taken from the table, accepted and ordered printed in full in the Proceedings.

After several announcements had been made by the Secretary, the Society proceeded at 11 o'clock to the consideration of the scientific papers.

TITLES AND ABSTRACTS OF PAPERS PRESENTED IN GENERAL SESSION AND
DISCUSSIONS THEREON

STRATIGRAPHY OF RED BEDS OF NEW MEXICO

BY N. H. DARTON

(*Abstract*)

The author presented an outline of results of detailed study of part of Red Beds area of New Mexico during the past summer. The investigation was mainly to determine areas in which chemical deposition had continued longest. Outcrop zones were followed continuously and stratigraphic changes traced in detail. The results show the equivalence of formations differentiated in various areas and throw much light on conditions of sedimentation during Pennsylvania-Triassic time.

DISCUSSION

Dr. WHITMAN CROSS: The sedimentary section described by Mr. Darton is very different in some particulars from that which has been studied in much detail in the adjacent portion of Colorado. In the analysis of the New Mexico sections it will be helpful to identify two horizons which have been found in Colorado to represent important stratigraphic breaks. One of these is at the base of the vertebrate-bearing Upper Triassic sediments; the other is at the base of the La Plata Jurassic sandstone.

The Jurassic and Pennsylvania rocks of the southern Colorado section are white or gray in prevalent colors. Red is mainly confined to the Triassic and Permian beds. In view of these and other well known variations in the distribution of a notable reddish color in Paleozoic and Mesozoic beds of the Rocky Mountain region, it seems undesirable to continue the use of the term "Red Beds" for the sediments of a particular region. It has not the value in correlation once assumed for it.

Prof. D. W. JOHNSON: From the Cerrillos region, New Mexico, I have described two series of Red Beds of a similar appearance only a few miles apart, one of Upper Cretaceous or Laramie age, the other belonging to the group described by Mr. Darton. Some bitter discussions were waged by the earlier workers in this region as to the stratigraphic position of "the Red Beds" near Cerrillos, the disputants not recognizing that they had observed distinct formations. This emphasizes the need, just pointed out by Doctor Cross, of qualifying the term "Red Beds" in such manner as to avoid confusion.

Presented in full without notes. The paper was briefly discussed further by Prof. R. D. Salisbury.

SOLAR HYPOTHESIS OF CLIMATIC CHANGES

BY ELLSWORTH HUNTINGTON

(Abstract)

At the last meeting of the Society the writer presented an hypothesis of the possible relation of solar activity to various terrestrial phenomena. Further study has convinced him that the hypothesis should be divided into two distinct parts whose degree of probability is widely different. The facts presented as to earthquakes may perhaps indicate some relationship between such phenomena and changes in the sun, but any such relationship is evidently highly complicated, and the data now at hand scarcely suffice to warrant a working hypothesis along these lines. On the other hand, further investigation of the relation of the sun to terrestrial climate brings out some striking agreements.

In all scientific work the normal process is to determine the causes of present phenomena and then to ascertain whether past phenomena of a similar nature may have been due to similar causes working on a different scale. In the study of geological climates the apparent gap between the great changes of geological times and the minor variations which are now in progress has greatly restricted this method of study. Measurements of the rate of growth of trees in California during the past 3,000 years, however, together with other lines of research, seem to show that the supposed gap between the minor changes of the present and the great changes of the past is bridged by intermediate phenomena of almost every grade. Therefore there seems to be strong reason for applying the normal scientific method of investigating the causes of present climatic changes and then determining how far the same causes may apply to the past.

The chief objections to the solar hypothesis have been (1) its indefiniteness, (2) the supposed inadequacy of observed solar changes to produce any appreciable meteorological phenomena, (3) the lack of any direct evidence that the

mean temperature of the sun has varied in the past, (4) the limited degree to which meteorological and solar relationships have as yet been detected, and (5) the contradictory nature of much of the evidence in regions outside the tropics.

In the light of recent discoveries these objections seem to lose much of their force. In the first place, the heat of the sun is concentrated in certain portions of the earth's surface according to the seasons. From this it would be expected that extra-tropical regions, where the concentration is less than in equatorial regions, would not show the same effect as those where the sun acts more directly. The work of Arctowski seems to indicate that variations in temperature move over the earth in waves, and that an increase in heat in a given region within the tropics may not appear noticeably in other regions until after a considerable lapse of time. If such a delay really occurs, it would account for much of the apparent contradiction between equatorial and extra-tropical regions.

The absence of direct agreement between solar and terrestrial phenomena may be accounted for in part in another way. The recent work of Humphreys, Fowle, and Abbott seems to show that the presence of volcanic dust in the atmosphere may exclude a measurable amount of solar radiation. The disturbing element thus introduced does not seem to be sufficient to account for the main climatic variations during the period since observations are available, but it accounts for many apparent discrepancies between solar and terrestrial phenomena.

Among the various elements which combine to make up the earth's climate none is more difficult to explain than the cyclonic storms which dominate the weather of Europe and America. These have recently been studied by two new methods. The first is the measurement of the growth of trees, by which our knowledge of climatic variations is extended over a much wider range than hitherto, both in Europe and America. The second is Kullmer's method of analyzing the number of cyclones passing over different portions of the temperate zone. Both methods appear to show a direct relationship between the number of sun-spots and the number of storms. Melldrum and others have shown a similar relationship in the case of tropical hurricanes. Moreover, the work of Kullmer shows that not only the number of storms, but their concentration in certain areas varies in response to sun-spots. Hence it appears that changes in solar spottedness, even though unaccompanied by any great change in the mean solar temperature, may influence the circulation of the earth's atmosphere and thus produce distinct changes of climate. The terrestrial changes, also, do not seem to demand any great change in the earth's mean temperature for the redistribution of solar and equatorial temperatures occasioned by a shifting of the location of storm tracks, and a change in their number would cause pronounced climatic variations, even if the mean temperature changed but slightly.

Presented in full without notes.

VOTE OF THANKS

A most hearty vote of thanks was passed to the authorities of Princeton University, the Department of Geology, and the local committee for

the ample accommodations provided for the meeting, the excellent preparatory work with reference to all the details of the sessions, and the arrangements made for the dispatch of business and the comfort of the visitors, and to the local Fellows for their generous hospitality. Particular mention was made of Prof. Gilbert van Ingen, on whom fell the brunt of the preparatory work and the conduct of the local arrangements.

The general session adjourned about 12.20 o'clock p. m.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE FIRST SECTION
AND DISCUSSIONS THEREON

The first section convened at 2.25 o'clock p. m., with President Eugene A. Smith in the chair and E. O. Hovey acting as secretary.

*OCCURRENCE OF GLACIAL DRIFT ON THE MAGDALEN ISLANDS*¹

BY J. W. GOLDTHWAIT

(Abstract)

These islands, which lie in the Gulf of Saint Lawrence, 50 miles northwest of Cape Breton, have been reported by James Richardson (1881), Robert Chalmers (1895), and Dr. John M. Clarke (1910) to be non-glaciated. During a rapid reconnaissance last summer the discovery was made of glacial boulder-clay containing soled and striated stones of both local and foreign derivation. Some of this evidence of glaciation will be exhibited and its value discussed in the face of the seemingly contradictory evidence presented by earlier observers.

Presented by title in the absence of the author.

*EVIDENCE OF A GLACIAL ICE-DAM IN THE ALLEGHENY RIVER BETWEEN
WARREN, PENNSYLVANIA, AND TIONESTA, PENNSYLVANIA*

BY G. FREDERICK WRIGHT

(Abstract)

The high level glacial gravel deposits on the east side of Conewango Creek at Warren, Pennsylvania, which were originally supposed to rest on a rock shelf, prove on closer examination to be continuous deposits from the bottom of the valley up. The course taken by the glacial stream which laid down these glacial deposits has been a puzzling one, until in a recent examination of the locality it was discovered that the more southern one of these gravel terraces, beginning near the golf links east of Warren, runs for a mile or more up the Allegheny Valley to the mouth of Glade Run, thus showing that the current was aiming toward the well known Tionesta outlet, in which there

¹ With the permission of the Director of the Geological Survey of Canada.

were extensive fluvial deposits of glacial age at Stoneham and Clarendon. The only way in which the current could thus have been deflected at that elevation would be by a temporary ice obstruction below Warren. From numerous considerations, it is evident that this obstruction was in the early part of the Glacial epoch, thus throwing doubt on the distance of the col that had to be eroded at Thompsons and emphasizing our conception of the extent of preglacial erosion in this region.

Presented by title in the absence of the author.

PREGLACIAL MIAMI AND KENTUCKY RIVERS

BY N. M. FENNEMAN

(Abstract)

It is generally agreed that the preglacial Ohio flowed north of Cincinnati to near Hamilton, Ohio (20 miles), and commonly supposed that it flowed thence west and south to the present mouth of the Miami and from there on had its present course. This has been disputed by Girard Fowke, who believes that the preglacial Ohio flowed north from Cincinnati along the line of the Miami (reversed). He depicts Kentucky River as continuing from its present mouth along the line of the Ohio and Miami rivers (reversed) to near Hamilton, Ohio, there joining the stream mentioned. The paper here presented takes up the evidences concerning these three rivers under the following heads: (1) The depth of the rock-floor at various places. (2) The width and apparent age of the valleys at different points. (3) The angles at which tributaries join their mains. (4) Asymmetrical form of divides as indicating recent drainage changes. The conclusion is reached that the preglacial Ohio flowed west from Hamilton, Ohio, instead of continuing northward, but that the present Ohio trough at Madison, Indiana, is the result of recent drainage changes.

Presented in abstract from manuscript.

DISCUSSION

Mr. FRANK LEVERETT suggested that the asymmetry near Madison is probably due to the Muscatatuck drainage being in part postglacial. The narrowness near Madison is at a place where the bluffs contain a much thicker bed of resistant limestone than at narrows near Cincinnati. It may not be necessary, therefore, to assume an old col to occur there.

Professor FENNEMAN replied to Mr. Leverett: In regard to the assumption that the rock-floor of the Ohio declines in altitude westward from the mouth of the Kentucky. There has been much drilling in the channel at Madison on account of the prospective dam and locks. Such borings have not revealed a rock trough as low as that known at the mouth of the Kentucky. The argument based on the narrowness of the valley at Madison is made stronger by a consideration of the undissected character of the adjacent uplands. This tends to confirm the conclusion that the Ohio trough at that point is recent.

DELAWARE TERRACES

BY N. H. WINCHELL

(Abstract)

In this paper the author critically examined the report of Prof. R. D. Salisbury and the conclusions to which he comes as to the correlation of the terraces below the glacial moraine south to Trenton. He pointed out the inconsistencies of that scheme—a scheme which is based on the dominant idea that the terraces as far as Trenton are due essentially to the action of the floods of the Wisconsin ice-epoch. The author called attention to the presence of an older drift in New Jersey, extending as far south as Trenton, called “Columbian” or “Pensauken,” which he parallelized with the Kansan, and to this epoch he assigned the “high terraces” of Salisbury, and to the Wisconsin he attributed but little of the accumulation of the well known Delaware terraces. He called attention to the necessarily flooded stages of the Delaware at the dates of the Glacial epochs which have been found, in the central western part of the country, to have occurred in the interval between the Kansan and the Wisconsin epochs, and to these epochs he assigned the yellow sands which are distributed copiously over older terraces at Trenton and northward nearly to the latitude of the Wisconsin moraine.

Read in abstract from manuscript.

SUBLACUSTRINE GLACIAL EROSION IN MONTANA

BY WILLIAM M. DAVIS

(Abstract)

Chief among the results of a Shaler Memorial Fund study in the summer of 1913 is the following: The great Kootenay-Pend'Oreille Glacier, which overdeepened the trough of Kootenay Lake in Canada, crossed the International Boundary into the United States and there divided into three branches. One branch ascended the upper valley of Clark Fork southeastward in northwestern Montana for 100 miles and barred its waters, which thereupon rose in a large and very irregular lake of fluctuating level, the faint shorelines of which indicate a maximum depth of 1,000 or 1,200 feet and an altitude of about 4,000 feet. Near its middle this branch glacier oversteepened the valley sides to heights of 1,000 feet or more; near its end to heights of 600 or 300 feet. If the greatest depth of the lake was contemporaneous with the greatest advance of the ice, as seems probable, the terminal part of the branch glacier must have done its erosive work while deeply submerged in 1,000 feet of lake water.

Presented in full without notes.

GLACIAL LAKE MISSOULA

BY R. W. STONE

(Abstract)

A large and irregular ice-dammed lake which filled a great part of the drainage basin of Clark Ford, in western Montana, was named and described by J. T. Pardee in 1910. His observations were mainly in the Bitterroot Valley. This paper gave evidence of the extent of Lake Missoula in Flathead Indian reservation, together with a description of an abandoned course of Flathead River. The large arm of Lake Missoula River which lay in the Flathead reservation was connected through its life with the arm in Bitterroot Valley by way of Missoula River Canyon near Paradise, and at its highest stage by a col at Evaro, 10 miles west of Missoula. The Northern Pacific Railway enters the reservation through this col. The greatest depth of the lake within the reservation was 1,500 feet at Perma and 1,300 feet in the vicinity of Flathead Lake. Lake-cut benches are common throughout the reservation. Sediment was deposited to a depth of more than 200 feet. Granite boulders indicate floating icebergs.

Previous to glaciation Flathead River flowed west 10 miles from the present position of the Big Arm of Flathead Lake, then south through Little Bitterroot Valley. This course was barred by a terminal moraine, and the present stream cuts through a moraine at the lower end of the lake and reaches its former course 20 miles south of the moraine.

Presented in abstract from notes.

PHYSIOGRAPHIC RELATIONS OF SERPENTINE, WITH SPECIAL REFERENCE TO
THE SERPENTINE STOCK OF STATEN ISLAND, NEW YORK

BY WILLIAM OTIS CROSBY

(Abstract)

The serpentine stock of Staten Island holds the formal relation of a monadnock to the Cretaceous peneplain, here buried beneath the coastal plain sediments. That it is a true residuary relief or erosion remnant is shown to be extremely improbable. Likewise mechanical (fracture and slip) faulting does not afford an adequate explanation. But this, it is believed, is found in the generally accepted view that this great body of essentially structureless serpentine has originated in the progressive, downward alteration of a stock of some massive, basic, magnesian, igneous rock, such as peridotite. Of this alteration hydration, with the resultant great expansion, is here the most important phase; and the expansion, which may amount to 40 per cent, must take place mainly upward or in the direction to give it the maximum topographic value. We have here a species of chemical as distinguished from mechanical faulting, and a new physiographic type, a variety of auto-relief not heretofore clearly recognized. Comparison with the spine or obelisk (pelélith) of Mont Pelé is suggested, and this comparison suggests the name *statenlith* for the new type, which is further shown to include other than

serpentine reliefs. A general classification of reliefs makes more clear the dynamic and structural relations of the *statenliths*. The chronologic and stratigraphic relations of the type example are also discussed.

Read in full from manuscript.

DISCUSSION

Dr. E. O. HOVEY remarked that the spine of Mont Pelé could not be regarded as the elevated or extruded plug of a volcano, but rather as the residue left by explosions of vapor which carried away portions of an exuding dome of lava which had solidified before it formed an ordinary flow.

EROSIVE POTENTIAL OF DESERT WATERS

BY CHARLES KEYES

(Abstract)

Since the origin of the dominant relief features in arid lands has been so long and persistently accounted for wholly on the hypothesis of general stream corrasion—by a process differing only in degree from that displayed in a normal humid climate—we may, with advantage, quantitatively measure some of the actual effects as presented under conditions of aridity, at the same time noting some of the limitations which are necessarily placed on water action by the exigencies of the desert. From consideration of the erosional modifications demanded by the special climatic conditions imposed by deficient rainfall, it follows that the gradational effects of the aqueous agencies must be assumed at the outset to be far below that which is commonly expected of them. Consideration is briefly given to the subjects of desert run-off, sheet-flood action, through-flowing rivers, piedmont arroyos, mountain streams, inland seas, ephemeral lakes, playas, salinas, and ground-water level.

Presented by title in the absence of the author.

SUBMARINE TOPOGRAPHY IN GLACIER BAY, ALASKA¹

BY LAWRENCE MARTIN

(Abstract)

During the summer of 1913 a National Geographic Society party studied submarine topography in Glacier Bay, especially in Tarr, Muir, Queen, and Tidal inlets.

Tarr Inlet is 816 to 1,320 feet deep, in contrast with about 600 feet in outer Glacier Bay. Nineteen years ago the thickness of Grand Pacific Glacier at the international boundary, 12 miles from the glacier terminus of 1894, was over 3,000 feet. The fiord is broadly U-shaped below, as above, sealevel. The longitudinal section shows irregularities impossible for a river-carved and

¹ Presented by permission of Henry Gannett, chairman of the Research Committee of the National Geographic Society.

submerged trench. Delta filling has gone on rapidly since the fiord was exposed by glacial retreat.

In Muir Inlet the eastern bay near Adams Glacier, 132 to 315 feet deep, has the submerged hanging valley relationship to the main fiord, with a discordance of about 600 feet. North of the ice-front of 1892 the depth of water is 936 to 1,152 feet. Only 21 years ago the ice was 2,500 feet thick at the site of the terminal cliff of Muir Glacier in 1913, 9 miles north of the ice-front of Reid's time.

Judging by (a) the exhumed forest floor discovered in 1913 near Muir Glacier, (b) the stumps of trees there and in Tarr Inlet, and (c) the drumlin-like shapes of ice-sculptured outwash gravels, the main work of glacial erosion was performed during the ancient, prolonged ice-flood stage rather than the modern, brief advance, which buried the lately exhumed forests and which probably had its maximum between 1794 and 1814. From this it is argued that vast lapse of time is necessary for the sculpture of fiords and of submerged hanging valleys, which in Glacier Bay are believed to have been carved chiefly by ice rather than running water, and produced with the land essentially at its present level.

Presented in full without notes. The paper was discussed by Messrs. N. H. Winchell and H. F. Reid.

*BURIED GORGE OF THE HUDSON RIVER AND GEOLOGIC RELATIONS OF
HUDSON SYPHON OF THE CATSKILL AQUEDUCT*

BY W. O. CROSBY

(Abstract)

Physiographic history:

- The Cretaceous peneplain.
- The Miocene baselevel.
- The Pliocene baselevel.
- The Pliocene gorge of the Hudson.
- The Pleistocene elevation.
- The Pleistocene gorge of the Hudson.
- Glaciation and glacial erosion.
- Glacial and postglacial deposits.

Bedrock geology:

- Nature of the bedrock.
- Joint structure.
- Thrust faults and shear zones.
- Transverse faults.
- Recent faulting.
- Gorge of the Hudson not a graben.

Storm-King-Breakneck section of the gorge:

- Contours.
- Depth.
- Deposits.

The Hudson gorge in the vicinity of New York:

The Pennsylvania tunnel profile.

Correlation of the bedrock channels.

Confirmation of the deep Pleistocene channel.

Nature of the bedrock floor of the Hudson south of the Highlands.

Possible bearing of differential elevation.

Presented by title.

The section adjourned.

ABSTRACTS OF PAPERS PRESENTED BEFORE THE THIRD SECTION AND DISCUSSION THEREON

The third section met at 2.40 o'clock p. m., with Vice-President James F. Kemp in the chair and F. R. Van Horn acting as secretary.

COMPOSITION OF BORNITE AND ITS RELATION TO OTHER SULFOMINERALS

BY EDWARD H. KRAUS

(Abstract)

As the result of a new analysis of exceptionally well crystallized bornite and a study of the published analyses of the mineral, the composition of bornite is shown to vary considerably. It is, however, possible to establish a definite series extending from chalcopyrite to chalcocite, the minerals of the series conforming to one general formula. This general formula seems also to underlie the composition of practically all the minerals, which are usually interpreted as sulfoferrites, arsenites, etcetera.

Presented in abstract without notes.

DISCUSSION

Dr. J. E. POGUE pointed out the importance of metallographic examination of sulphide minerals subjected to analysis because of the prevalence of intergrown microscopic impurities. Such examination needs also to be undertaken under high magnification, for impurities not visible at magnifications of, say, X 40 appear at X 200. The divergence of older bornite analyses may be due in part to microscopic impurities. The bornite formulas of Professor Kraus, showing increasing copper content, suggest the relation of the principal copper minerals of the Mount Lyell Mine, Tasmania, which, in the order of their formation, are cupriferous pyrite, chalcopyrite, bornite, and chalcocite—an order corresponding to decreasing iron and increasing copper content.

Prof. J. V. LEWIS said that all teachers of mineralogy would be indebted to Doctor Kraus if some simple arrangement in the formulæ of complex sulphosalts, such as suggested by Doctor Kraus, could be proven.

Prof. F. R. VAN HORN: We are indebted to Doctor Kraus for a new viewpoint on the composition of complex sulphosalts. Doctor Kraus quoted analysis of pearceite and polybasite, discussed by Penfield, and later by Van Horn. I do not think that I am willing to admit that such a series exists here as might be drawn from the two formulæ proposed, but that the older formulæ suggested by Heinrich Rose for polybasite and by Penfield for pearceite are not correct.

Doctor KRAUS answered Dr. Pogue's questions and was also inclined to believe that two formulæ did not exist for polybasite and pearceite instead of one, as contended by Van Horn.

Prof. James F. Kemp participated in the discussion.

GENESIS OF GLAUCONITE

BY CHASE PALMER²⁹

(Abstract)

A dense cloudy substance brought to the surface along with the water of a well 2,000 feet deep, newly sunk at Charleston, South Carolina, was studied. The composition of this substance corresponds very closely with that of glauconite.

The qualities of the water in the well are compared with the qualities of the river waters of the Piedmont Plateau and Coastal Plain.

The coprecipitation of ferric hydrate, potassium oxide, and silicic acid, all of which are essential constituents of glauconite, may take place in the absence of organic matter. An explanation is offered of the mode of formation of glauconite in marine glauconitic shells.

Presented by title in the absence of the author.

CRYSTALLIZATION OF CERTAIN PYROXENE-BEARING ARTIFICIAL MELTS

BY N. L. BOWEN³⁰

(Abstract)

The melts dealt with contain lime-magnesian pyroxenes, and certain of them show the crystallization of olivine (forsterite) at relatively high temperatures and its later resorption or reaction with the melt at lower temperatures. There is therefore an interesting analogy with some recorded natural occurrences.

Presented in abstract without notes.

²⁹ Introduced by T. Wayland Vaughan.

³⁰ Introduced by C. N. Fenner.

*PHYSICAL-CHEMICAL SYSTEM, LIME-ALUMINA-SILICA AND ITS GEOLOGICAL
SIGNIFICANCE*

BY FRED E. WRIGHT AND G. A. RANKIN

(Abstract)

The laboratory work on this system is now practically finished. A model, illustrating the temperature equilibrium conditions for the system, has been made and serves to indicate the course of crystallization of the different phases which occur throughout the system. The bearing of the relations thus obtained on petrogenetic theory was outlined briefly.

Presented in abstract without notes. Remarks were made by Messrs. C. W. Parmelee and J. E. Pogue.

The Society adjourned at 4.15 o'clock p. m.

CONSTITUTION AND BY-LAWS

REFERENCES TO ADOPTION AND CHANGES

The provisional Constitution under which the Society was organized was approved August 15, 1888, and adopted December 27, 1888 (see Bulletin, volume 1, pages 7-8). These rules were elaborated and the revised Constitution and By-Laws were adopted December 27, 1889 (volume 1, pages 536, 571-578).

Several minor changes have been made in these rules, which are on record in the Bulletin as follows: Changes in the Constitution: December, 1894, volume 6, page 432; December, 1897, volume 9, page 400; December, 1909, volume 21, page 19. Changes in the By-Laws: December, 1891, volume 3, page 470; December, 1893, volume 5, pages 553-554; December, 1894, volume 6, page 432; December, 1903, volume 14, page 535; December, 1909, volume 21, page 19.

CONSTITUTION

ARTICLE I

NAME

This Society shall be known as THE GEOLOGICAL SOCIETY OF AMERICA.

ARTICLE II

OBJECT

The object of this Society shall be the promotion of the Science of Geology in North America.

ARTICLE III

MEMBERSHIP

The Society shall be composed of Fellows, Correspondents, and Patrons.

1. Fellows shall be persons who are engaged in geological work or in teaching geology.

Fellows admitted without election under the provisional Constitution shall be designated as Original Fellows on all lists or catalogues of the Society.

2. Correspondents shall be persons distinguished for their attainments in Geological Science and not resident in North America.

3. Patrons shall be persons who have bestowed important favors upon the Society.

4. Fellows alone shall be entitled to vote or hold office in the Society.

ARTICLE IV

OFFICERS

1. The Officers of the Society shall consist of a President, First, Second, and Third Vice-Presidents, a Secretary, a Treasurer, an Editor, and six Councilors.

These officers, together with the Presidents for the next preceding three years, shall constitute an Executive Committee, which shall be called the Council.

2. The President shall discharge the usual duties of a presiding officer at all meetings of the Society and of the Council. He shall take cognizance of the acts of the Society and of its officers, and cause the provisions of the Constitution and By-Laws to be faithfully carried into effect.

3. The first Vice-President shall assume the duties of President in case of the absence or disability of the latter. The Second Vice-President shall assume the duties of President in case of the absence or disability of both the President and First Vice-President. The Third Vice-President shall assume the duties of President in case of the absence or disability of the President and the First and Second Vice-Presidents.

4. The Secretary shall keep the records of the proceedings of the Society, and a complete list of the Fellows, with the dates of their election and disconnection with the Society. He shall also be the secretary of the Council.

The Secretary shall cooperate with the President in attention to the ordinary affairs of the Society. He shall attend to the preparation, printing and mailing of circulars, blanks and notifications of elections and meetings. He shall superintend other printing ordered by the Society or by the President, and shall have charge of its distribution, under the direction of the Council.

The Secretary, unless other provision be made, shall also act as Editor of the publications of the Society, and as Librarian and Custodian of the property.

5. The Treasurer shall have the custody of all funds of the Society. He shall keep account of receipts and disbursements in detail, and this shall be audited as hereinafter provided.

6. The Editor shall supervise all matters connected with the publication of the transactions of the Society under the direction of the Council.

7. The Council is clothed with executive authority and with the legislative powers of the Society in the intervals between its meetings; but no extraordinary act of the Council shall remain in force beyond the next following stated meeting without ratification by the Society. The Council shall have control of the publications of the Society, under provisions of the By-Laws and of resolutions from time to time adopted. They shall receive nominations for Fellows, and, on approval by them, shall submit such nominations to the Society for action. They shall have power to fill vacancies *ad interim* in any of the offices of the Society.

8. *Terms of office.*—The President and Vice-Presidents shall be elected annually, and shall not be eligible to re-election more than once until after an interval of three years after retiring from office.

The Secretary, Treasurer, and Editor shall be eligible to re-election without limitation.

The term of office of the Councilors shall be three years; and these officers shall be so grouped that two shall be elected and two retire each year. Councilors retired shall not be re-eligible till after the expiration of a year.

ARTICLE V

VOTING AND ELECTIONS

1. All elections shall be by ballot. To elect a Fellow, Correspondent or Patron, or impose any special tax, shall require the assent of nine-tenths of all Fellows voting.

2. Voting by letter may be allowed.

3. *Election of Fellows.*—Nominations for fellowship may be made by two Fellows according to a form to be provided by the Council. One of these Fellows must be personally acquainted with the nominee and his qualifications for membership. The Council will submit the nominations received by them, if approved, to a vote of the Society in the manner provided in the By-Laws. The result may be announced at any stated meeting; after which notice shall be sent out to Fellows elect.

4. *Election of officers.*—Nominations for office shall be made by the Council. The nominations shall be submitted to a vote of the Society in the same manner as nominations for fellowship. The results shall be announced at the Annual Meeting; and the officers thus elected shall enter upon duty at the adjournment of the meeting.

ARTICLE VI

MEETINGS

1. The Society shall hold at least one stated meeting a year, in the winter season. The date and place of the Winter Meeting shall be fixed by the Council, and announced each year within three months after the adjournment of the preceding Winter Meeting. The program of each meeting shall be determined by the Council, and announced beforehand, in its general features. The details of the daily sessions shall also be arranged by the Council.

2. The Winter Meeting shall be regarded as the Annual Meeting. At this, elections of officers shall be declared, and the officers elect shall enter upon duty at the adjournment of the meeting.

3. Special meetings may be called by the Council, and must be called upon the written request of twenty Fellows.

4. Stated meetings of the Council shall be held coincidently with the stated meetings of the Society. Special meetings may be called by the President at such times as he may deem necessary.

5. *Quorum.*—At meetings of the Society a majority of those registered in attendance shall constitute a quorum. Five shall constitute a quorum of the Council.

ARTICLE VII

PUBLICATION

The serial publications of the Society shall be under the immediate control of the Council.

ARTICLE VIII

SECTIONS

Any group of Fellows representing a particular branch of geology may, with consent of the Council, organize as a section of the Society with separate con-

constitution and by-laws, provided that nothing in such constitution and by-laws conflict with the constitution and by-laws of the Geological Society of America, in letter or spirit, and provided that such constitution and by-laws and all amendments thereto shall have been approved by the Council.

ARTICLE IX

AMENDMENTS

1. This Constitution may be amended at any annual meeting by a three-fourths vote of all the Fellows, provided that the proposed amendment shall have been submitted in print to all Fellows at least three months previous to the meeting.

2. By-laws may be made or amended by a majority vote of the Fellows present and voting at any annual meeting, provided that printed notice of the proposed amendment or by-law shall have been given to all Fellows at least three months before the meeting.

BY-LAWS

CHAPTER I

OF MEMBERSHIP

1. No person shall be accepted as a Fellow unless he pay his initiation fee, and the dues for the year, within three months after notification of his election. The initiation fee shall be ten (10) dollars and the annual dues ten (10) dollars, the latter payable on or before the annual meeting in advance; but a single prepayment of one hundred and fifty (150) dollars shall be accepted as commutation for life. A Fellow in good standing, however, who has paid annual dues for not less than fifteen (15) years may commute further dues and become a Life Fellow by making a single payment of one hundred (100) dollars.

2. The sums paid in commutation of dues shall be covered into the Publication Fund.

3. An arrearage in payment of annual dues shall deprive a Fellow of the privilege of taking part in the management of the Society and of receiving the publications of the Society. An arrearage continuing over two (2) years shall be construed as notification of withdrawal.

4. Any person eligible under Article III of the Constitution may be elected Patron upon the payment of one thousand (1,000) dollars to the Publication Fund of the Society.

CHAPTER II

OF OFFICIALS

1. The President shall countersign, if he approves, all duly authorized accounts and orders drawn on the Treasurer for the disbursement of money.

2. The Secretary, until otherwise ordered by the Society, shall perform the duties of Editor, Librarian, and Custodian of the property of the Society.

3. The Society may elect an Assistant Secretary.

4. The Treasurer shall give bonds, with two good sureties approved by the Council, in the sum of five thousand dollars, for the faithful and honest performance of his duties and the safe-keeping of the funds of the Society. He may deposit the funds in bank at his discretion, but shall not invest them without authority of the Council. His accounts shall be balanced as on the thirtieth day of November of each year.

5. In the selection of Councilors the various sections of North America shall be represented as far as practicable.

6. The minutes of the proceedings of the Council shall be subject to call by the Society.

7. The Council may transact its business by correspondence during the intervals between its stated meetings; but affirmative action by a majority of the Council shall be necessary in order to make action by correspondence valid.

CHAPTER III

OF ELECTION OF MEMBERS

1. Nominations for fellowship may be proposed at any time on blanks to be supplied by the Secretary.

2. The *form* for the nomination of Fellows shall be as follows:

In accordance with his desire, we respectfully nominate for Fellow of the Geological Society of America:

Full name; degrees; address; occupation; branch of Geology now engaged in, work already done and publications made.

(Signed by at least two Fellows.)

The form when filled is to be transmitted to the Secretary.

3. The Secretary will bring all nominations before the Council, and the Council will signify its approval or disapproval of each.

4. At least a month before one of the stated meetings of the Society the Secretary will mail a printed list of all approved nominees to each Fellow, accompanied by such information as may be necessary for intelligent voting; but an informal list of the candidates shall be sent to each Fellow at least two weeks prior to distribution of the ballots.

5. The Fellows receiving the list will signify their approval or disapproval of each nominee, and return the lists to the Secretary.

6. At the next stated meeting of the Council the Secretary will present the lists and the Council will canvass the returns.

7. The Council, by unanimous vote of the members in attendance, may still exercise the power of rejection of any nominee whom new information shows to be unsuitable for fellowship.

8. At the next stated meeting of the Society the Council shall declare the results.

9. Correspondents and Patrons shall be nominated by the Council, and shall be elected in the same manner as Fellows.

CHAPTER IV

OF ELECTION OF OFFICERS

1. The Council shall prepare a list of nominations for the several offices, which list will constitute the regular ticket. The ticket must be approved by a majority of the entire Council. The nominee for President shall not be a member of the Council. One of the nominees for vice-president shall be the nominee for the presidency of the Paleontological Society which has been organized as a section under Article VIII of the Constitution.

2. The list shall be mailed to the Fellows, for their information, at least nine months before the Annual Meeting. Any five Fellows may forward to the Secretary other nominations for any or all offices. All such nominations reaching the Secretary at least 40 days before the Annual Meeting shall be printed, together with the names of the nominators, as special tickets. The regular and special tickets shall then be mailed to the Fellows at least 25 days before the Annual Meeting.

3. The Fellows will send their ballots to the Secretary in double envelopes, the outer envelope bearing the voter's name. At the Winter Meeting of the

Council, the Secretary will bring the returns of ballots before the Council for canvass, and during the Winter Meeting of the Society the Council shall declare the result.

4. In case a majority of all the ballots shall not have been cast for any candidate for any office, the Society shall by ballot at such Winter Meeting proceed to make an election for such office from the two candidates having the highest number of votes.

CHAPTER V

OF FINANCIAL METHODS

1. No pecuniary obligation shall be contracted without express sanction of the Society or the Council. But it is to be understood that all ordinary, incidental, and running expenses have the permanent sanction of the Society, without special action.

2. The creditor of the Society must present to the Treasurer a fully itemized bill, certified by the official ordering it, and approved by the President. The Treasurer shall then pay the amount out of any funds not otherwise appropriated, and the receipted bill shall be held as his voucher.

3. At each annual meeting, the President shall call upon the Society to choose two Fellows, not members of the Council, to whom shall be referred the books of the Treasurer, duly posted and balanced to the close of November thirtieth, as specified in the By-Laws, Chapter II, clause 4. The Auditors shall examine the accounts and vouchers of the Treasurer, and any member or members of the Council may be present during the examination. The report of the Auditors shall be rendered to the Society before the adjournment of the meeting, and the Society shall take appropriate action.

CHAPTER VI

OF PUBLICATIONS

1. The publications are in charge of the Council and under its control.

2. One copy of each publication shall be sent to each Fellow, Correspondent, and Patron, and each author shall receive thirty (30) copies of his memoir.

CHAPTER VII

OF THE PUBLICATION FUND

1. The Publication Fund shall consist of donations made in aid of publication, and of the sums paid in commutation of dues, according to the By-Laws, Chapter I, clause 2.

2. Donors to this fund, not Fellows of the Society, in the sum of two hundred dollars, shall be entitled, without charge, to the publications subsequently appearing.

CHAPTER VIII

OF ORDER OF BUSINESS

1. The Order of Business at Winter Meetings shall be as follows:

- (1) Call to order by the presiding officer.
- (2) Introductory ceremonies.

- (3) Report of the Council (including report of the officers).
 - (4) Appointment of the Auditing Committee.
 - (5) Declaration of the vote for officers, and election by the meeting in case of failure to elect by the Society through transmitted ballots.
 - (6) Declaration of the vote for Fellows.
 - (7) Deferred business.
 - (8) New business.
 - (9) Announcements.
 - (10) Necrology.
 - (11) Reading of scientific papers.
2. At an adjourned session the order shall be resumed at the place reached on the previous adjournment, but new business will be in order before the reading of scientific papers.
3. At the Summer Meeting the items of business under numbers (3), (4), (5), (10) shall be omitted.
4. At any Special Meeting the order of business shall be numbers (1), (2), (3), (9), followed by the special business for which the meeting was called.

PUBLICATION RULES OF THE GEOLOGICAL SOCIETY OF AMERICA

(Adopted by the Council April 21, 1891; Revised April 30, 1894, May, 1904, and February 5, 1910)

GENERAL PROVISIONS

SECTION 1. The Council shall annually appoint from their own number a Publication Committee, consisting of the Secretary, the Treasurer, the Editor, and two others, whose duties shall be to determine the disposition of matter offered for publication, except as provided in section 12; to determine the expediency, in view of the financial condition of the Society, of publishing any matter accepted on its merits; to exercise general oversight of the matter and manner of publication; to determine the share of the cost of publication (including illustrations) to be borne by the author when it becomes necessary to divide cost between the Society and the author; to adjudicate any questions relating to publication that may be raised from time to time by the Editor or by the Fellows of the Society; and in general to act for the Council in all matters pertaining to publication. (Cons., Art. IV, 7; Art. VII; By-Laws, chap. VI.)

2. The duties of the Editor are to receive material offered for publication; to examine and submit it, with estimates of cost, to the Publication Committee; to publish all material accepted by the Council or Publication Committee; to revise proofs in connection with authors; to prepare lists of contents and general indexes; to audit bills for printing and illustrating; and to perform all other duties connected with publication not assigned to other officers. (Cons., Art. IV, 6; Rules, Sec. 16.)

3. The duties of the Secretary include the preparation of a record of the proceedings of each meeting of the Society in form for publication, and the custody, distribution, sale, exchange or other authorized disposition of the publications. (Cons., Art. IV, 4; By-Laws, chap. II, 2.)

4. Special committees may be appointed by the Council or the Publication Committee to examine and report on any matter offered for publication. (Rules, Sec. 11.)

THE BULLETIN

TITLE AND GENERAL CHARACTER

5. The Society shall publish a serial record of its work entitled "Bulletin of the Geological Society of America."

6. The Bulletin shall be published in quarterly parts, consecutively paged for each volume. The parts shall be suitably designated and each shall bear a title setting forth the contents and authorship, the seal and imprint of the Society and the date of publication.

7. The closing quarterly part of each volume shall contain an index, paged consecutively with the body of the volume; and it shall be accompanied by a volume title-page and lists of contents and illustrations, together with lists of

the publications of the Society and such other matter as the Publication Committee may deem necessary, all arranged under Roman pagination.

MATTER OF THE BULLETIN

8. The matter published in the Bulletin shall comprise (1) communications presented at meetings by title or otherwise; (2) communications or memoirs not presented before the Society; (3) abstracts of papers read before the Society, prepared or revised for publication by authors; (4) reports of discussions held before the Society, prepared or revised for publication by authors; (5) proceedings of the meetings of the Society prepared by the Secretary; (6) plates, maps, and other illustrations necessary for the proper understanding of communications; (7) lists of Officers and Fellows, Constitution, By-Laws, resolutions of permanent character, rules relating to procedure, to publication, and to other matters, etcetera, and (8) indexes, title-pages, and lists of contents for each volume.

9. Abstracts, reports of discussion, or other matter purporting to emanate from any author shall not be published unless prepared or revised by the author.

10. Manuscript designed for publication in the Bulletin must be complete as to copy for text and illustration, except by special arrangement between the author and the Council or Publication Committee; it must be perfectly legible (preferably typewritten) and preceded by a table of contents (section 15). The cost of necessary revision of copy or reconstruction of illustrations shall be assessed on the author.

11. The Editor shall examine matter designated for publication, and shall prepare an itemized estimate of the cost of publication and convey the whole to the Publication Committee. The Publication Committee shall then scrutinize the communication with reference, first, to relevancy; second, to scientific value; third, to literary character, and, fourth, to cost of publication, including revision. For advice with reference to the relevancy, scientific value, and literary character of any communication the Publication Committee may refer it to a special committee of their own number or of the Society at large or may call to their aid from outside one or more experts. Questions of disagreement between the Editor and authors shall be referred to the Publication Committee and appeal may be taken to the Council.

12. Communications from non-fellows shall be published only by specific authority from the Council.

13. Communications from Fellows not presented at regular meetings of the Society shall be published only upon unanimous vote of the Publication Committee, except by specific authority from the Council.

14. Matter offered for publication becomes thereby the property of the Society, and shall not be published elsewhere prior to publication in the Bulletin, except by consent of the Publication Committee.

DETAILS OF THE BULLETIN

15. The matter of each memoir shall be classified by subjects, and the classification suitably indicated by subtitles; and a list of contents shall be arranged; and such memoir may, at the option of the Publication Committee, contain an alphabetical index, provided the author prepare and pay for it.

16. Proofs of text and illustrations shall be submitted to authors whenever practicable; but printing shall not be delayed by reason of absence or incapacity of authors more than one week beyond the time required for transmission by mail. Complete proofs of the proceedings of meetings shall be sent to the Secretary, and proofs of papers and abstracts contained therein and exceeding one-half page in length shall be sent also to authors.

17. The cost of proof corrections in excess of five per cent on the cost of printing may be charged to authors.

18. Unless the author of a memoir objects thereto, the discussion upon his communication shall be printed at the end thereof, with a suitable reference in the list of contents. In case the author objects to this arrangement, the discussion shall be printed in the closing number of the volume.

19. The author of each memoir occupying eight pages or more of text in the body of the Bulletin shall receive 30 "separates" without charge, and may order through the Editor any edition of exactly similar separates at an advance of ten per cent. on the cost of paper, presswork and binding; and no author's separates of such memoirs shall be issued except in this regular form.

20. Authors of papers, abstracts, or discussions less than eight printed pages in length may order, through the Editor, at an advance of ten per cent. on the cost of paper, presswork, binding and necessary composition, any number of extra copies, provided they bear the original pagination and a printed reference to the serial and volume from which they are extracted.

21. The Editor shall keep a record of all publications issued wholly or in part under the auspices of the Society, whether they be author's editions of memoirs, author's extracts from proceedings, or any other matter printed from type originally composed for the Bulletin.

DIRECTIONS TO PRINTER

22. Each memoir of the Bulletin shall begin, under its proper title, on an odd-numbered page bearing at its head the title of the serial, the volume number, the part number, the limiting pages, the plates, and the date of publication, together with a list of contents. Each memoir shall be accompanied by the illustrations pertaining to it, the plates numbered consecutively for the volume.

23. The author's separates of each memoir shall be enclosed in a cover bearing at the head of its title-page the title of the serial, the volume number, the limiting pages, and the numbers of the contained plates; in its upper-central part a title indicating the contents and authorship; in its lower-central part the seal of the Society; and at the bottom the imprint of the Society. (See also Sections 19 and 20.)

24. The bottom of each signature and each initial page will bear a signature mark giving an abbreviated title of the serial, the volume, and the year; and every page (except volume title-page) shall be numbered, the initial and sub-title pages in parentheses at bottom.

25. The page-head titles shall be: on even-numbered pages, name of author and catch title of paper; on odd-numbered pages, catch title to contents of page.

26. The date of publication of each brochure shall be the day upon which the last form is locked and put on the press.

27. The type used in printing the Bulletin shall be as follows: For memoirs, body, long primer, 6-to-pica leads; extracts, brevier, 8-to-pica leads; footnotes, nonpareil, set solid; titles, long primer caps, with small caps for author's name; subtitles, long primer caps, small caps, italic, etcetera, as far as practicable; for designation of cuts, nonpareil caps and italics, and for legends, nonpareil, Roman, set solid; for lists of contents of brochures, brevier, 6-to-pica leads, a new line to an entry, running indentation; for volumes, the same, except 4-to-pica leads and names of authors in small caps; for indexes, nonpareil, set solid, double column, leaders, catch words in small caps, with spaces between initial letters. For serial titles, on initial pages, brevier block caps, with corresponding small caps for volume designation, etcetera; on covers, the same, except for page heads long primer caps; for serial designation, long primer; for brochure designation, pica caps; special title and author's name, etcetera, long primer and brevier caps; no frame on cover. No change in type shall be made to adjust matter to pages.

28. Volumes, plates, and cuts in text shall be numbered in Arabic; Roman numeration shall be used only in signature marks, and in paging the lists of contents, etcetera, arranged for binding at the beginning of the volume.

29. Imprimatur of Editor, on volume title-page; imprimatur of Council and Publication Committee, on obverse of volume title-page; imprimatur of Secretary, on initial pages and covers of brochures of proceedings. Printer's card, in fine type on obverse of title-page.

30. The paper shall be for body of volume, 70-pound toned paper, folding to 16 x 25 centimeters; for plates, good quality plate paper, smooth-surfaced, white, cut to 6½ x 10 inches for single plates; for covers smooth-surfaced, fine quality 70-pound light-buff manila paper.

31. The sheets of the brochures shall be stitched with thread; single page plates shall be stitched with the sheets of the brochure; folding plates may be either gummed or stitched (mounted on stubs if necessary); covers shall be gummed.

EDITION, DISTRIBUTION, AND PRICE

32. The regular edition shall be 660 copies in the regular quarterly form and 40 copies separately in covers of each memoir occupying eight pages or more of text. Each author of a memoir occupying not less than eight pages of text shall receive 30 copies of his memoir gratis. If two or more authors contribute to a memoir brochure of eight pages or more in length, the edition shall be enlarged so as to give each author 30 copies. (By-Laws, chap. VI, 2.)

33. The undistributed residue of separates shall be held for sale.

34. The Bulletin shall be sent free to Fellows of the Society not in arrears for dues, and also to exchanging institutions. (By-Laws, chap. I, 3.)

35. The price of the Bulletin shall be as follows: To Fellows, libraries, and institutions, and to individuals not residing in North America, \$7.50 per volume; to individuals residing in North America and who are not Fellows, \$10. The price of each brochure shall be a multiple of five cents, and shall be, to Fellows, one cent per page plus three cents per plate and to the public an advance of fifty per cent. on the price to Fellows. The prices of the separate brochures and of the quarterly parts may be found in the front of each volume.

REGISTER OF THE PRINCETON MEETING, 1913

FELLOWS

FRANK D. ADAMS
R. C. ALLEN
HENRY M. AMI
GEORGE H. ASHLEY
W. W. ATWOOD
FLORENCE BASCOM
RAY SMITH BASSLER
GEORGE F. BECKER
EDWARD WILBER BERRY
S. W. BEYER
JOHN A. BOWNOCKER
ALFRED H. BROOKS
BARNUM BROWN
CHARLES W. BROWN
HENRY A. BUEHLER
D. D. CAIRNES
FRANK CARNEY
E. C. CASE
W. B. CLARK
JOHN M. CLARKE
ARTHUR P. COLEMAN
A. R. CROOK
WILLIAM O. CROSBY
WHITMAN CROSS
N. H. DARTON
CHARLES A. DAVIS
WILLIAM M. DAVIS
ARTHUR L. DAY
FRANK W. DE WOLF
RICHARD E. DODGE
JOHN A. DRESSER
CHARLES R. DRYER
HERMAN L. FAIRCHILD
OLIVER C. FARRINGTON
N. M. FENNEMAN
C. A. FISHER
AUGUST F. FOERSTE

JAMES W. GOLDTHWAIT
AMADEUS W. GRABAU
WALTER GRANGER
U. S. GRANT
HERBERT E. GREGORY
BAIRD HALBERSTADT
RICHARD R. HICE
WILLIAM H. HOBBS
THOMAS C. HOPKINS
WILLIAM O. HOTCHKISS
EDMUND OTIS HOVEY
ERNEST HOWE
ELLSWORTH HUNTINGTON
JOSEPH P. IDDINGS
ROBERT T. JACKSON
DOUGLAS W. JOHNSON
ARTHUR KEITH
JAMES F. KEMP
FRANK H. KNOWLTON
EDWARD H. KRAUS
GEORGE F. KUNZ
WILLIS T. LEE
FRANK LEVERETT
J. VOLNEY LEWIS
WILLIAM LIBBEY
FREDERICK B. LOOMIS
ALBERT P. LOW
RICHARD SWAN LULL
CURTIS F. MARBUT
GEORGE C. MARTIN
LAWRENCE MARTIN
EDWARD B. MATHEWS
W. D. MATTHEW
GEORGE P. MERRILL
ARTHUR M. MILLER
BENJAMIN L. MILLER
WILLET G. MILLER

WILLIAM J. MILLER
 FRED H. MOFFIT
 ELWOOD S. MOORE
 IDA HELEN OGILVIE
 HENRY F. OSBORN
 SIGNEY PAIGE
 R. A. F. PENROSE, JR.
 GEORGE H. PERKINS
 LOUIS V. PIRSSON
 JOSEPH E. POGUE
 ALBERT H. PURDUE
 PERCY E. RAYMOND
 H. F. REID
 WILLIAM NORTH RICE
 HEINRICH RIES
 RUDOLPH RUEDEMANN
 ROLLIN D. SALISBURY
 FREDERICK W. SARDESON
 THOMAS E. SAVAGE
 CHARLES SCHUCHERT
 WILLIAM B. SCOTT
 C. E. SIEBENTHAL
 WILLIAM J. SINCLAIR
 JOSEPH T. SINGEWALD
 EUGENE A. SMITH
 GEORGE OTIS SMITH
 PHILIP S. SMITH

CHARLES H. SMYTH, JR.
 J. W. SPENCER
 J. STANLEY-BROWN
 T. W. STANTON
 J. J. STEVENSON
 RALPH W. STONE
 GEORGE W. STOSE
 FRANK B. TAYLOR
 M. W. TWITCHELL
 E. O. ULRICH
 FRANK R. VAN HORN
 GILBERT VAN INGEN
 THOMAS W. VAUGHAN
 CHARLES D. WALCOTT
 THOMAS L. WALKER
 STUART WELLER
 LEWIS G. WESTGATE
 DAVID WHITE
 I. C. WHITE
 GEORGE R. WIELAND
 H. S. WILLIAMS
 A. W. G. WILSON
 N. H. WINCHELL
 JOHN E. WOLFF
 FREDERIC E. WRIGHT
 G. FREDERIC WRIGHT

FELLOWS-ELECT

C. A. HARTNAGEL

C. A. REEDS

MIGNON TALBOT

In addition to the foregoing, there were registered at the meeting 14 members of the Paleontological Society, 15 members of the Association of American Geographers, and 106 visitors, including wives of members and specially invited assistants and students.

OFFICERS, CORRESPONDENTS, AND FELLOWS OF THE
GEOLOGICAL SOCIETY OF AMERICA

OFFICERS FOR 1914

President:

GEORGE F. BECKER, Washington, D. C.

Vice-Presidents:

WALDEMAR LINDGREN, Boston, Mass.

HORACE B. PATTON, Golden, Colo.

HENRY F. OSBORN, New York, N. Y.

Secretary:

EDMUND OTIS HOVEY, American Museum of Natural History, New
York, N. Y.

Treasurer:

WM. BULLOCK CLARK, Johns Hopkins University, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Librarian:

F. R. VAN HORN, Cleveland, Ohio

Councilors:

(Term expires 1914)

S. W. BEYER, Ames, Iowa

ARTHUR KEITH, Washington, D. C.

(Term expires 1915)

WHITMAN CROSS, Washington, D. C.

WILLET G. MILLER, Toronto, Canada

(Term expires 1916)

R. A. F. PENROSE, JR., Philadelphia, Pa.

W. W. ATWOOD, Cambridge, Mass.

MEMBERSHIP, 1914

CORRESPONDENTS

- CHARLES BARROIS, Lille, France. December, 1909.
 W. C. BRÖGGER, Christiania, Norway. December, 1909.
 GIOVANNI CAPELLINI, Bologna, Italy. December, 1910.
 BARON GERHARD DE GEER, Stockholm, Sweden. December, 1910.
 SIR ARCHIBALD GEIKIE, Hasslemere, England. December, 1909.
 ALBERT HEIM, Zürich, Switzerland. December, 1909.
 EMANUEL KAYSER, Marburg, Germany. December, 1909.
 W. KILIAN, Grenoble, France. December, 1912.
 H. ROSENBUSCH, Heidelberg, Germany. December, 1910.³¹
 EDUARD SUESS, Vienna, Austria. December, 1909.
 J. J. H. TEALL, London, England. December, 1912.
 EMIL TIETZE, Vienna, Austria. December, 1910.
 TH. TSCHERNYSCHEW, St. Petersburg, Russia. December, 1910.³²

FELLOWS

*Indicates Original Fellow (see article III of Constitution)

- CLEVELAND ABBE, JR., U. S. Weather Bureau, Washington, D. C. August, 1899.
 FRANK DAWSON ADAMS, McGill University, Montreal, Canada. Dec., 1889.
 GEORGE I. ADAMS, Pei Yang University, Tientsin, China. December, 1902.
 JOSÉ GUADALUPE AGUILERA, Instituto Geologico, Mexico, Mexico. Aug., 1896.
 WILLIAM CLINTON ALDEN, U. S. Geological Survey, Washington, D. C. December, 1909.
 TRUMAN H. ALDRICH, Birmingham, Ala. May, 1889.
 R. C. ALLEN, State Geologist, Lansing, Mich. December, 1911.
 HENRY M. AMI, Geological and Natural History Survey of Canada, Ottawa, Canada. December, 1889.
 FRANK M. ANDERSON, State Mining Bureau, 2604 Ætna St., Berkeley, Cal. June, 1902.
 ROBERT VAN VLECK ANDERSON, care W. J. Carr, 32 Broadway, New York, N. Y. December, 1911.
 PHILIP ARGALL, First National Bank Building, Denver, Colo. August, 1896.
 RALPH ARNOLD, 923 Union Oil Building, Los Angeles, Cal. December, 1904.
 GEORGE HALL ASHLEY, U. S. Geological Survey, Washington, D. C. Aug., 1895.
 WALLACE WALTER ATWOOD, University of Chicago, Chicago, Ill. Dec., 1909.
 RUFUS MATHER BAGG, JR., Lawrence College, Appleton, Wis. December, 1896.
 HARRY FOSTER BAIN, 667 Howard St., San Francisco, Cal. December, 1895.
 MANLEY BENSON BAKER, School of Mining, Kingston, Ontario. Dec., 1911.
 S. PRENTISS BALDWIN, 2930 Prospect Ave., Cleveland, Ohio. August, 1895.
 SYDNEY H. BALL, 71 Broadway, New York City. December, 1905.
 ERWIN HINCKLEY BARBOUR, University of Nebraska, Lincoln, Neb. Dec., 1896.
 ALFRED ERNEST BARLOW, 328 Roslyn Ave., Westmont, Montreal, Canada. December, 1906.
 JOSEPH BARRELL, Yale University, New Haven, Conn. December, 1902.
 GEORGE H. BARTON, Boston Society of Natural History, Boston, Mass. August, 1890.

³¹ Died January 20, 1914.

³² Died January 15, 1914.

- FLORENCE BASCOM, Bryn Mawr College, Bryn Mawr, Pa. August, 1894.
RAY SMITH BASSLER, U. S. National Museum, Washington, D. C. Dec., 1906.
EDSON SUNDERLAND BASTIN, U. S. Geological Survey, Washington, D. C. December, 1909.
WILLIAM S. BAYLEY, University of Illinois, Urbana, Ill. December, 1888.
*GEORGE F. BECKER, U. S. Geological Survey, Washington, D. C.
JOSHUA W. BEEDE, Indiana University, Bloomington, Ind. December, 1902.
ROBERT BELL, Geological Survey, Department of Mines, Ottawa, Canada. May, 1889.
CHARLES P. BERKEY, Columbia University, New York, N. Y. August, 1901.
EDWARD WILBER BERRY, Johns Hopkins University, Baltimore, Md. Dec., 1909.
SAMUEL WALKER BEYER, Iowa Agricultural College, Ames, Iowa. Dec., 1896.
ARTHUR B. BIBBINS, Goucher College, Baltimore, Md. December, 1903.
ALBERT S. BICKMORE, 64th St. and Central Park West, New York, N. Y. December, 1889.
ELIOT BLACKWELDER, University of Wisconsin, Madison, Wis. Dec., 1908.
JOHN M. BOUTWELL, 1323 De la Vine St., Santa Barbara, Cal. Dec., 1905.
JOHN ADAMS BOWNOCKER, Ohio State University, Columbus, Ohio. Dec., 1904.
*JOHN C. BRANNER, Leland Stanford, Jr., University, Stanford University, Cal.
EDWIN BAYER BRANSON, University of Missouri, Columbia, Mo. Dec., 1911.
ALBERT PERRY BRIGHAM, Colgate University, Hamilton, N. Y. December, 1893.
REGINALD W. BROCK, Geological Survey, Department of Mines, Ottawa, Canada. December, 1904.
ALFRED HULSE BROOKS, U. S. Geological Survey, Washington, D. C. Aug., 1899.
AMOS P. BROWN, University of Pennsylvania, Philadelphia, Pa. Dec., 1905.
BARNUM BROWN, American Museum of Natural History, New York, N. Y. December, 1910.
CHARLES WILSON BROWN, Brown University, Providence, R. I. Dec., 1908.
HENRY ANDREW BUEHLER, Rolla, Mo. December, 1909.
BERT S. BUTLER, U. S. Geological Survey, Washington, D. C. December, 1912.
G. MONTAGUE BUTLER, School of Mines, Golden, Colo. December, 1911.
CHARLES BUTTS, U. S. Geological Survey, Washington, D. C. December, 1912.
DE LORNE DONALDSON CAIRNES, Geological Survey Branch, Department of Mines, Ottawa, Canada. December, 1912.
FRED HARVEY HALL CALHOUN, Clemson College, S. C. December, 1909.
HENRY DONALD CAMPBELL, Washington and Lee University, Lexington, Va. May, 1889.
MARIUS R. CAMPBELL, U. S. Geological Survey, Washington, D. C. Aug., 1892.
STEPHEN REID CAPPS, JR., U. S. Geological Survey, Washington, D. C. Dec., 1911.
FRANK CARNEY, Granville, Ohio. December, 1908.
ERMINE C. CASE, University of Michigan, Ann Arbor, Mich. December, 1901.
GEORGE HALCOTT CHADWICK, St. Lawrence University, Canton, N. Y. December, 1911.
ROLLIN T. CHAMBERLIN, University of Chicago, Chicago, Ill. December, 1913.
*T. C. CHAMBERLIN, University of Chicago, Chicago, Ill.
CLARENCE RAYMOND CLAGHORN, Tacoma, Wash. August, 1891.
FREDERICK G. CLAPP, 502 Fitzsimons Bldg., Pittsburgh, Pa. December, 1905.
*WILLIAM BULLOCK CLARK, Johns Hopkins University, Baltimore, Md.
JOHN MASON CLARKE, Albany, N. Y. December, 1897.
HERDMAN F. CLELAND, Williams College, Williamstown, Mass. Dec., 1905.

- J. MORGAN CLEMENTS, Room 1707, 42 Broadway, New York City. Dec., 1894.
 COLLIER COBB, University of North Carolina, Chapel Hill, N. C. Dec., 1894.
 ARTHUR P. COLEMAN, Toronto University, Toronto, Canada. December, 1896.
 GEORGE L. COLLIE, Beloit College, Beloit, Wis. December, 1897.
 ARTHUR J. COLLIER, U. S. Geological Survey, Washington, D. C. June, 1902.
- *THEODORE B. COMSTOCK, Van Nuys Bldg., Los Angeles, Cal.
 EUGENE COSTE, 1943 11th St., West, Calgary, Alberta, Canada. Dec., 1906.
 ALJA ROBINSON CROOK, State Museum of Natural History, Springfield, Ill. December, 1898.
- *WILLIAM O. CROSBY, Massachusetts Institute of Technology, Boston, Mass.
 WHITMAN CROSS, U. S. Geological Survey, Washington, D. C. May, 1889.
 GARRY E. CULVER, 1104 Wisconsin St., Stevens Point, Wis. December, 1891.
 EDGAR R. CUMINGS, Indiana University, Bloomington, Ind. August, 1901.
- *HENRY P. CUSHING, Adelbert College, Cleveland, Ohio.
 REGINALD A. DALY, Harvard University, Cambridge, Mass. December, 1905.
 EDWARD SALISBURY DANA, Yale University, New Haven, Conn. Dec., 1908.
- *NELSON H. DARTON, U. S. Geological Survey, Washington, D. C.
 CHARLES ALBERT DAVIS, U. S. Bureau of Mines, Washington, D. C. Dec., 1910.
- *WILLIAM M. DAVIS, Harvard University, Cambridge, Mass.
 ARTHUR LOUIS DAY, Geophysical Laboratory, Carnegie Institution, Washington, D. C. December, 1909.
 DAVID T. DAY, U. S. Geological Survey, Washington, D. C. August, 1891.
 BASHFORD DEAN, Columbia University, New York, N. Y. December, 1910.
 ORVILLE A. DERBY, Serv. Geol. & Mineral. d'Brazil, Praia Vermillia, Rio de Janeiro, Brazil. December, 1890.
 FRANK WILBRIDGE DE WOLF, Urbana, Ill. December, 1909.
- *JOSEPH S. DILLER, U. S. Geological Survey, Washington, D. C.
 EDWARD V. D'INVILLIERS, 518 Walnut St., Philadelphia, Pa. December, 1888.
 RICHARD E. DODGE, Teachers' College, New York, N. Y. August, 1897.
 NOAH FIELDS DRAKE, Fayetteville, Arkansas. December, 1898.
 JOHN ALEXANDER DRESSER, 10 Forest Ave., Saulte Ste. Marie, Ontario, Canada. December, 1906.
 CHARLES R. DRYER, Oak Knoll, Fort Wayne, Ind. August, 1897.
- *EDWIN T. DUMBLE, 1306 Main St., Houston, Texas.
 ARTHUR S. EAKLE, University of California, Berkeley, Cal. December, 1899.
 CHARLES R. EASTMAN, Carnegie Museum, Pittsburgh, Pa. December, 1895.
 EDWIN C. ECKEL, Munsey Building, Washington, D. C. December, 1905.
- *BENJAMIN K. EMERSON, Amherst College, Amherst, Mass.
 WILLIAM HARVEY EMMONS, University of Minnesota, Minneapolis, Minn. December, 1912.
 JOHN EYERMAN, Oakhurst, Easton, Pa. August, 1891.
 HAROLD W. FAIRBANKS, Berkeley, Cal. August, 1892.
- *HERMAN L. FAIRCHILD, University of Rochester, Rochester, N. Y.
 OLIVER C. FARRINGTON, Field Museum of Natural History, Chicago, Ill. December, 1895.
 NEVIN M. FENNEMAN, University of Cincinnati, Cincinnati, Ohio. Dec., 1904.
 CLARENCE NORMAN FENNER, Geophysical Laboratory, Washington, D. C. December, 1911.
 CASSIUS ASA FISHER, 711 Ideal Building, Denver, Colo. December, 1908.
 AUGUST F. FOERSTE, 128 Rockwood Ave., Dayton, Ohio. December, 1899.
 MYRON LESLIE FULLER, 185 Spring St., Brockton, Mass. December, 1898.

- HENRY STEWART GANE, Santa Barbara, Cal. December, 1896.
- JAMES H. GARDNER, Kentucky Geological Survey, Lexington, Ky. Dec., 1911.
- RUSSELL D. GEORGE, University of Colorado, Boulder, Colo. December, 1906.
- *GROVE K. GILBERT, U. S. Geological Survey, Washington, D. C.
- ADAM CAPEN GILL, Cornell University, Ithaca, N. Y. December, 1888.
- L. C. GLENN, Vanderbilt University, Nashville, Tenn. June, 1900.
- JAMES WALTER GOLDTHWAIT, Dartmouth College, Hanover, N. H. Dec., 1909.
- CHARLES H. GORDON, University Library, University of Tennessee, Knoxville, Tenn. August, 1893.
- CLARENCE E. GORDON, Massachusetts Agricultural College, Amherst, Mass. December, 1913.
- CHARLES NEWTON GOULD, 408 Terminal Bldg., Oklahoma City, Okla. December, 1904.
- AMADEUS W. GRABAU, Columbia University, New York, N. Y. December, 1898.
- WALTER GRANGER, American Museum of Natural History, New York, N. Y. December, 1911.
- ULYSSES SHERMAN GRANT, Northwestern University, Evanston, Ill. Dec., 1890.
- JOHN SHARSHALL GRASTY, University of Virginia, University, Va. Dec., 1911.
- LOUIS C. GRATON, Harvard University, Cambridge, Mass. December, 1913.
- HERBERT E. GREGORY, Yale University, New Haven, Conn. August, 1901.
- GEORGE P. GRIMSLEY, Geological Survey of West Virginia, Martinsburg, W. Va. August, 1895.
- LEON S. GRISWOLD, Plymouth, Mass. August, 1902.
- FREDERIC P. GULLIVER, 1112 Morris Bldg., Philadelphia, Pa. August, 1895.
- ARNOLD HAGUE, U. S. Geological Survey, Washington, D. C. May, 1889.
- BAIRD HALBERSTADT, Pottsville, Pa. December, 1909.
- GILBERT D. HARRIS, Cornell University, Ithaca, N. Y. December, 1903.
- JOHN BURCHMORE HARRISON, Georgetown, British Guiana. June, 1902.
- CHRIS. A. HARTNAGEL, State Museum, Albany, N. Y. December, 1913.
- JOHN B. HASTINGS, 1480 High St., Denver, Colo. May, 1889.
- *ERASMUTH HAWORTH, University of Kansas, Lawrence, Kans.
- C. WILLARD HAYES, Compania Mexicana de Petroleo "El Aguila," Tampico, Mexico. May, 1889.
- OSCAR H. HERSHEY, Kellogg, Idaho. December, 1909.
- RICHARD R. HICE, Beaver, Pa. December, 1903.
- FRANK A. HILL, 1315 Mahantango St., Pottsville, Pa. May, 1889.
- *ROBERT T. HILL, Federal Bldg., Los Angeles, Cal.
- RICHARD C. HILLS, Denver, Colo. August, 1894.
- HENRY HINDS, U. S. Geological Survey, Washington, D. C. December, 1912.
- *CHARLES H. HITCHCOCK, Honolulu, Hawaiian Islands.
- WILLIAM HERBERT HOBBS, University of Michigan, Ann Arbor, Mich. August, 1891.
- *LEVI HOLBROOK, P. O. Box 536, New York, N. Y.
- WILLIAM JACOB HOLLAND, Carnegie Museum, Pittsburgh, Pa. December, 1910.
- ARTHUR HOLLICK, New York Botanical Garden, Bronx Park, New York City. August, 1893.
- *JOSEPH A. HOLMES, U. S. Bureau of Mines, Washington, D. C.
- THOMAS C. HOPKINS, Syracuse University, Syracuse, N. Y. December, 1894.
- WILLIAM OTIS HOTCHKISS, State Geologist, Madison, Wis. December, 1911.
- *EDMUND OTIS HOVEY, American Museum of Natural History, New York, N. Y.
- *HORACE C. HOVEY, Newburyport, Mass.

- ERNEST HOWE, 75 Kay St., Newport, R. I. December, 1903.
 LUCIUS L. HUBBARD, Houghton, Mich. December, 1894.
 ELLSWORTH HUNTINGTON, Yale University, New Haven, Conn. Dec., 1906.
 LOUIS HUSSAKOF, American Museum of Natural History, New York, N. Y. December, 1910.
 JOSEPH P. IDDINGS, Brinklow, Md. May, 1889.
 JOHN D. IRVING, Yale University, New Haven, Conn. December, 1905.
 A. WENDELL JACKSON, 432 Saint Nicholas Ave., New York, N. Y. Dec., 1888.
 ROBERT T. JACKSON, 56 Bay State Road, Boston, Mass. August, 1894.
 THOMAS AUGUSTUS JAGGAR, JR., Hawaiian Volcano Observatory, Territory of Hawaii, U. S. A. December, 1906.
 MARK S. W. JEFFERSON, Michigan State Normal College, Ypsilanti, Mich. December, 1904.
 ALBERT JOHANNSEN, University of Chicago, Chicago, Ill. December, 1908.
 DOUGLAS WILSON JOHNSON, Columbia University, New York, N. Y. Dec., 1906.
 ALEXIS A. JULIEN, South Harwich, Mass. May, 1889.
 FRANK JAMES KATZ, U. S. Geological Survey, Washington, D. C. Dec., 1912.
 GEORGE FREDERICK KAY, State University of Iowa, Iowa City, Iowa. Dec., 1908.
 ARTHUR KEITH, U. S. Geological Survey, Washington, D. C. May, 1889.
 *JAMES F. KEMP, Columbia University, New York, N. Y.
 CHARLES ROLLIN KEYES, 944 Fifth St., Des Moines, Iowa. August, 1890.
 EDWARD M. KINDLE, Victoria Memorial Museum, Ottawa, Canada. Dec., 1905.
 EDWIN KIRK, U. S. Geological Survey, Washington, D. C. December, 1912.
 CYRIL WORKMAN KNIGHT, Toronto, Ontario, Canada. December, 1911.
 ADOLPH KNOFF, U. S. Geological Survey, Washington, D. C. December, 1911.
 FRANK H. KNOWLTON, U. S. National Museum, Washington, D. C. May, 1889.
 EDWARD HENRY KRAUS, University of Michigan, Ann Arbor, Mich. June, 1902.
 HENRY B. KÜMMEL, Trenton, N. J. December, 1895.
 *GEORGE F. KUNTZ, 401 Fifth Ave., New York, N. Y.
 GEORGE EDGAR LADD, State College, N. M. August, 1891.
 LAWRENCE MORRIS LAMBE, Department of Mines, Ottawa, Canada. Dec., 1911.
 HENRY LANDES, University of Washington, University Station, Seattle, Wash. December, 1908.
 ALFRED C. LANE, Tufts College, Mass. December, 1889.
 ANDREW C. LAWSON, University of California, Berkeley, Cal. May, 1889.
 WILLIS THOMAS LEE, U. S. Geological Survey, Washington, D. C. Dec., 1903.
 CHARLES K. LEITH, University of Wisconsin, Madison, Wis. Dec., 1902.
 ARTHUR G. LEONARD, State University of North Dakota, Grand Forks, N. Dak. December, 1901.
 FRANK LEVERETT, Ann Arbor, Mich. August, 1890.
 JOSEPH VOLNEY LEWIS, Rutgers College, New Brunswick, N. J. Dec., 1906.
 WILLIAM LIBBEY, Princeton University, Princeton, N. J. August, 1899.
 WALDEMAR LINDGREN, Massachusetts Institute of Technology, Boston, Mass. August, 1890.
 MIGUEL A. R. LISBOA, Irrigation and Water Supply Service, Rio de Janeiro, Brazil. December, 1913.
 FREDERICK BREWSTER LOOMIS, Amherst College, Amherst, Mass. Dec., 1909.
 GEORGE DAVIS LOUDERBACK, University of California, Berkeley, Cal. June, 1902.
 ROBERT H. LOUGHRIDGE, University of California, Berkeley, Cal. May, 1889.
 ALBERT P. LOW, Department of Mines, Ottawa, Canada. December, 1905.
 RICHARD SWANN LULL, Yale University, New Haven, Conn. December, 1909.

- SAMUEL WASHINGTON McCALLIE, Atlanta, Ga. December, 1909.
- HIRAM DEYER McCASKEY, U. S. Geological Survey, Washington, D. C. December, 1904.
- RICHARD G. McCONNELL, Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.
- JAMES RIEMAN MACFARLANE, Woodland Road, Pittsburgh, Pa. August, 1891.
- WILLIAM McINNES, Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.
- PETER McKELLAR, Fort William, Ontario, Canada. August, 1890.
- GEORGE ROGERS MANSFIELD, 2039 Park Road N. W., Washington, D. C. December, 1909.
- CURTIS F. MARBUT, State University, Columbia, Mo. August, 1897.
- VERNON F. MARSTERS, San Juancito, Honduras, C. A. August, 1892.
- GEORGE CURTIS MARTIN, U. S. Geological Survey, Washington, D. C. June, 1902.
- LAWRENCE MARTIN, University of Wisconsin, Madison, Wis. December, 1909.
- EDWARD B. MATHEWS, Johns Hopkins University, Baltimore, Md. Aug., 1895.
- W. D. MATTHEW, American Museum of Natural History, New York, N. Y. December, 1903.
- P. H. MELL, 165 East 10th St., Atlanta, Ga. December, 1888.
- WALTER C. MENDENHALL, U. S. Geological Survey, Washington, D. C. June, 1902.
- JOHN C. MERRIAM, University of California, Berkeley, Cal. August, 1895.
- *FREDERICK J. H. MERRILL, 624 Citizens' National Bank Bldg., Los Angeles, Cal.
- GEORGE P. MERRILL, U. S. National Museum, Washington, D. C. Dec., 1888.
- ARTHUR M. MILLER, State University of Kentucky, Lexington, Ky. Dec., 1897.
- BENJAMIN L. MILLER, Lehigh University, South Bethlehem, Pa. Dec., 1904.
- WILLET G. MILLER, Toronto, Canada. December, 1902.
- WILLIAM JOHN MILLER, Hamilton College, Clinton, N. Y. December, 1909.
- FRED HOWARD MOFFIT, U. S. Geological Survey, Washington, D. C. Dec., 1912.
- G. A. F. MOLENGRAAF, Technical High School, Delft, Holland. December, 1913.
- HENRY MONTGOMERY, University of Toronto, Toronto, Canada. Dec., 1904.
- ELWOOD S. MOORE, Pennsylvania State College, State College, Pa. Dec., 1911.
- MALCOLM JOHN MUNN, Clinton Bldg., Tulsa, Okla. December, 1909.
- *FRANK L. NASON, West Haven, Conn.
- DAVID HALE NEWLAND, Albany, N. Y. December, 1906.
- JOHN F. NEWSOM, Leland Stanford, Jr., University, Stanford University, Cal. December, 1899.
- WILLIAM H. NORTON, Cornell College, Mount Vernon, Iowa. December, 1895.
- CHARLES J. NORWOOD, State University, Lexington, Ky. August, 1894.
- IDA HELEN OGILVIE, Barnard College, Columbia University, New York, N. Y. December, 1906.
- CLEOPHAS C. O'HARRA, South Dakota School of Mines, Rapid City, S. Dak. December, 1904.
- DANIEL WEBSTER OHERN, University of Oklahoma, Norman, Okla. Dec., 1911.
- EZEQUIEL ORDONEZ, 2 a General Prim 43, Mexico, D. F., Mex. August, 1896.
- EDWARD ORTON, JR., Geological Survey of Ohio, Columbus, Ohio. Dec., 1909.
- HENRY F. OSBORN, American Museum of Natural History, New York, N. Y. August, 1894.
- SIDNEY PAIGE, U. S. Geological Survey, Washington, D. C. December, 1911.
- CHARLES PALACHE, Harvard University, Cambridge, Mass. August, 1897.
- WILLIAM A. PARKS, University of Toronto, Toronto, Canada. December, 1906.

- *HORACE B. PATTON, Colorado School of Mines, Golden, Colo.
 FREDERICK B. PECK, Lafayette College, Easton, Pa. August, 1901.
 RICHARD A. F. PENROSE, JR., 460 Bullitt Bldg., Philadelphia, Pa. May, 1889.
 GEORGE H. PERKINS, University of Vermont, Burlington, Vt.; State Geologist.
 June, 1902.
 JOSEPH H. PERRY, 276 Highland St., Worcester, Mass. December, 1888.
 OLAF AUGUST PETERSON, Carnegie Museum, Pittsburgh, Pa. December, 1910.
 WILLIAM CLIFTON PHALEN, U. S. Geological Survey, Washington, D. C. December, 1912.
 LOUIS V. PIRSSON, Yale University, New Haven, Conn. August, 1894.
 JOSEPH E. POGUE, U. S. Geological Survey, Washington, D. C. Dec., 1911.
 JOSEPH HYDE PRATT, North Carolina Geological Survey, Chapel Hill, N. C. December, 1898.
 LOUIS M. PRINDLE, U. S. Geological Survey, Washington, D. C. Dec., 1912.
 *CHARLES S. PROSSER, Ohio State University, Columbus, Ohio.
 WILLIAM FREDERICK PROUTY, University of Alabama, University, Ala. December, 1911.
 *RAPHAEL PUMPELLE, Newport, R. I.
 ALBERT HOMER PURDUE, State Geological Survey, Nashville, Tenn. Dec., 1904.
 FREDERICK LESLIE RANSOME, U. S. Geological Survey, Washington, D. C. August, 1895.
 PERCY EDWARD RAYMOND, Museum of Comparative Zoölogy, Cambridge, Mass. December, 1907.
 CHESTER A. REEDS, American Museum of Natural History, New York, N. Y. December, 1913.
 HARRY FIELDING REID, Johns Hopkins University, Baltimore, Md. Dec., 1892.
 WILLIAM NORTH RICE, Wesleyan University, Middletown, Conn. August, 1890.
 JOHN LYON RICH, University of Illinois, Urbana, Ill. December, 1912.
 CHARLES H. RICHARDSON, Syracuse University, Syracuse, N. Y. Dec., 1899.
 GEORGE BURR RICHARDSON, U. S. Geological Survey, Washington, D. C. December, 1908.
 HEINRICH RIES, Cornell University, Ithaca, N. Y. December, 1893.
 ELMER S. RIGGS, Field Museum of Natural History, Chicago, Ill. Dec., 1911.
 JESSE PERRY ROWE, University of Montana, Missoula, Mont. December, 1911.
 RUDOLPH RUEDEMANN, Albany, N. Y. December, 1905.
 JOHN JOSEPH RUTLEDGE, Experiment Station, Pittsburgh, Pa. Dec., 1911.
 ORESTES H. ST. JOHN, 1141 Twelfth St., San Diego, Cal. May, 1889.
 *ROLLIN D. SALISBURY, University of Chicago, Chicago, Ill.
 FREDERICK W. SARDESON, University of Minnesota, Minneapolis, Minn. December, 1892.
 THOMAS EDMUND SAVAGE, University of Illinois, Urbana, Ill. December, 1907.
 FRANK C. SCHRADER, U. S. Geological Survey, Washington, D. C. Aug., 1901.
 CHARLES SCHUCHERT, Yale University, New Haven, Conn. August, 1895.
 ALFRED REGINALD SCHULTZ, U. S. Geological Survey, Washington, D. C. December, 1912.
 WILLIAM B. SCOTT, Princeton University, Princeton, N. J. August, 1892.
 ARTHUR EDMUND SEAMAN, Michigan College of Mines, Houghton, Mich. December, 1904.
 HENRY M. SEELY, Middlebury College, Middlebury, Vt. May, 1889.
 ELIAS H. SELLARDS, Tallahassee, Fla. December, 1905.
 JOAQUIM CANDIDO DA COSTA SEÑA, State School of Mines, Ouro Preto, Brazil, December, 1908.

- GEORGE BURBANK SHATTUCK, Vassar College, Poughkeepsie, N. Y. Aug., 1899.
 EUGENE WESLEY SHAW, U. S. Geological Survey, Washington, D. C. Dec., 1912.
 SOLON SHEDD, State College of Washington, Pullman, Wash. Dec., 1904.
 EDWARD M. SHEPARD, 1403 Benton Ave., Springfield, Mo. August, 1901.
 WILL H. SHERZER, State Normal School, Ypsilanti, Mich. December, 1890.
 BOHUMIL SHIMEK, University of Iowa, Iowa City, Iowa. December, 1904.
 HERVEY WOODBURN SHIMER, Massachusetts Institute of Technology, Boston, Mass. December, 1910.
 CLAUDE ELLSWORTH SIEBENTHAL, U. S. Geological Survey, Washington, D. C. December, 1912.
 *FREDERICK W. SIMONDS, University of Texas, Austin, Texas.
 WILLIAM JOHN SINCLAIR, Princeton University, Princeton, N. J. Dec., 1906.
 JOSEPH THEOPHILUS SINGEWALD, Johns Hopkins University, Baltimore, Md. December, 1911.
 EARLE SLOAN, Charleston, S. C. December, 1908.
 BURNETT SMITH, Syracuse University, Skaneateles, N. Y. December, 1911.
 CARL SMITH, U. S. Geological Survey, Washington, D. C. December, 1912.
 *EUGENE A. SMITH, University of Alabama, University, Ala.
 GEORGE OTIS SMITH, U. S. Geological Survey, Washington, D. C. Aug., 1897.
 PHILIP S. SMITH, U. S. Geological Survey, Washington, D. C. Dec., 1909.
 WARREN DU PRÉ SMITH, Mining Bureau, Manila, Philippine Islands. December, 1909.
 W. S. TANGIER SMITH, Los Gatos, Cal. June, 1902.
 *JOHN C. SMOCK, Trenton, N. J.
 CHARLES H. SMYTH, JR., Princeton University, Princeton, N. J. Aug., 1892.
 HENRY L. SMYTH, Harvard University, Cambridge, Mass. August, 1894.
 ARTHUR COE SPENCER, U. S. Geological Survey, Washington, D. C. Dec., 1896.
 *J. W. SPENCER, 2019 Hillyer Place, Washington, D. C.
 FRANK SPRINGER, U. S. National Museum, Washington, D. C. December, 1911.
 JOSIAH E. SPURR, Bullitt Bldg., Philadelphia, Pa. December, 1894.
 JOSEPH STANLEY-BROWN, 26 Exchange Place, New York, N. Y. August, 1892.
 TIMOTHY WILLIAM STANTON, U. S. National Museum, Washington, D. C. August, 1891.
 CLINTON RAYMOND STAUFFER, Western Reserve University, Cleveland, Ohio. December, 1911.
 LLOYD WILLIAM STEPHENSON, U. S. Geological Survey, Washington, D. C. December, 1911.
 *JOHN J. STEVENSON, 215 West 101st St., New York, N. Y.
 RALPH WALTER STONE, U. S. Geological Survey, Washington, D. C. Dec., 1912.
 GEORGE WILLIS STOSE, U. S. Geological Survey, Washington, D. C. Dec., 1908.
 WILLIAM J. SUTTON, Victoria, B. C. August, 1901.
 CHARLES KEPHART SWARTZ, Johns Hopkins University, Baltimore, Md. December, 1908.
 JOSEPH A. TAFF, 712 Flood Building, San Francisco, Cal. August, 1895.
 MIGNON TALBOT, Mount Holyoke College, South Hadley, Mass. Dec., 1913.
 JAMES E. TALMAGE, University of Utah, Salt Lake City, Utah. Dec., 1897.
 FRANK B. TAYLOR, Fort Wayne, Ind. December, 1895.
 *JAMES E. TODD, 1224 Rhode Island St., Lawrence, Kans.
 CYRUS FISHER TOLMAN, JR., Leland Stanford, Jr., University, Stanford University, Cal. December, 1909.

- ARTHUR C. TROWBRIDGE, State University of Iowa, Iowa City, Iowa. December, 1913.
- *HENRY W. TURNER, Room 709 Mills Building, San Francisco, Cal.
- WILLIAM H. TWENHOFEL, University of Kansas, Lawrence, Kans. Dec., 1913.
- MAYVILLE WILLIAM TWITCHELL, State Geological Survey, Trenton, N. J. December, 1911.
- JOSEPH B. TYRRELL, Room 534, Confederation Life Building, Toronto, Canada. May, 1889.
- JOHAN A. UDDEN, University of Texas, Austin, Texas. August, 1897.
- EDWARD O. ULRICH, U. S. Geological Survey, Washington, D. C. Dec., 1903.
- JOSEPH B. UMPLEBY, U. S. Geological Survey, Washington, D. C. Dec., 1913.
- *WARREN UPHAM, Minnesota Historical Society, Saint Paul, Minn.
- *CHARLES R. VAN HISE, University of Wisconsin, Madison, Wis.
- FRANK ROBERTSON VAN HORN, Case School of Applied Science, Cleveland, Ohio. December, 1898.
- GILBERT VAN INGEN, Princeton University, Princeton, N. J. December, 1904.
- THOMAS WAYLAND VAUGHAN, U. S. Geological Survey, Washington, D. C. August, 1896.
- ARTHUR CLIFFORD VEACH, 47 Parliament St., S. W., London, England. Dec., 1906.
- *ANTHONY W. VOGDES, 2425 First St., San Diego, Cal.
- *M. EDWARD WADSWORTH, School of Mines, University of Pittsburgh, Pittsburgh, Pa.
- *CHARLES D. WALCOTT, Smithsonian Institution, Washington, D. C.
- THOMAS L. WALKER, University of Toronto, Toronto, Canada. Dec., 1903.
- CHARLES H. WARREN, Massachusetts Institute of Technology, Boston, Mass. December, 1901.
- HENRY STEPHENS WASHINGTON, Geophysical Laboratory, Washington, D. C. August, 1896.
- THOMAS L. WATSON, University of Virginia, Charlottesville, Va. June, 1900.
- CHARLES E. WEAVER, University of Washington, Seattle, Wash. Dec., 1913.
- WALTER H. WEED, 42 Broadway, New York, N. Y. May, 1889.
- CARROLL HARVEY WEGEMANN, U. S. Geological Survey, Washington, D. C. December, 1912.
- SAMUEL WEIDMAN, Wisconsin Geological and Natural History Survey, Madison, Wis. December, 1903.
- STUART WELLER, University of Chicago, Chicago, Ill. June, 1900.
- LEWIS G. WESTGATE, Ohio Wesleyan University, Delaware, Ohio.
- DAVID WHITE, U. S. National Museum, Washington, D. C. May, 1889.
- *ISRAEL C. WHITE, Morgantown, W. Va.
- GEORGE REBER WIELAND, Yale University, New Haven, Conn. December, 1910.
- FRANK A. WILDER, North Holston, Smyth County, Va. December, 1905.
- *EDWARD H. WILLIAMS, Jr., Woodstock, Vt.
- *HENRY S. WILLIAMS, Cornell University, Ithaca, N. Y.
- IRA A. WILLIAMS, Oregon School of Mines, Corvallis, Ore. December, 1905.
- BAILEY WILLIS, U. S. Geological Survey, Washington, D. C. December, 1889.
- ARTHUR B. WILMOTT, 404 Lumsden Building, Toronto, Canada. Dec., 1899.
- ALFRED W. G. WILSON, Department of Mines, Ottawa, Canada. June, 1902.
- ALEXANDER N. WINCHELL, University of Wisconsin, Madison, Wis. Aug., 1901.
- *HORACE VAUGHN WINCHELL, 505 Palace Building, Minneapolis, Minn.
- *NEWTON H. WINCHELL, 501 East River Road, Minneapolis, Minn.

- *ARTHUR WINSLOW, 131 State St., Boston, Mass.
 JOHN E. WOLFF, Harvard University, Cambridge, Mass. December, 1889.
 JOSEPH E. WOODMAN, New York University, New York, N. Y. Dec., 1905.
 ROBERT S. WOODWARD, Carnegie Institution of Washington, Washington, D. C.
 May, 1889.
 JAY B. WOODWORTH, Harvard University, Cambridge, Mass. December, 1895.
 CHARLES WILL WRIGHT, Ingurtozu, Arbus, Sardinia, Italy. December, 1909.
 FREDERIC E. WRIGHT, Geophysical Laboratory, Carnegie Institution, Wash-
 ington, D. C. December, 1903.
 *G. FREDERICK WRIGHT, Oberlin Theological Seminary, Oberlin, Ohio.
 GEORGE A. YOUNG, Geological Survey of Canada, Ottawa, Canada. Dec., 1905.

CORRESPONDENTS DECEASED

- A. MICHEL-LÉVY. Died September, 1911.
 FERDINAND ZERKEL. Died June 11, 1912.
 HERMAN CREDNER. Died July 22, 1913.

FELLOWS DECEASED

*Indicates Original Fellow (see article III of Constitution)

- *CHARLES A. ASHBURNER. Died December 24, 1889.
 CHARLES E. BEECHER. Died February 14, 1904.
 WILLIAM PHIPPS BLAKE. Died May 21, 1910.
 AMOS BOWMAN. Died June 18, 1894.
 ERNEST ROBERTSON BUCKLEY. Died January 19, 1912.
 *SAMUEL CALVIN. Died April 17, 1911.
 FRANKLIN R. CARPENTER. Died April 1, 1910.
 *J. H. CHAPIN. Died March 14, 1892.
 *EDWARD W. CLAYPOLE. Died August 17, 1901.
 GEORGE H. COOK. Died September 22, 1889.
 *EDWARD D. COPE. Died April 12, 1897.
 ANTONIO DEL CASTILLO. Died October 28, 1895.
 *JAMES D. DANA. Died April 14, 1895.
 GEORGE M. DAWSON. Died March 2, 1901.
 SIR J. WILLIAM DAWSON. Died November 19, 1899.
 CLARENCE EDWARD DUTTON. Died January 4, 1912.
 *WILLIAM B. DWIGHT. Died August 29, 1906.
 *GEORGE H. ELDRIDGE. Died June 29, 1905.
 *SAMUEL F. EMMONS. Died March 28, 1911.
 WILLIAM M. FONTAINE. Died April 29, 1913.
 *ALBERT E. FOOTE. Died October 10, 1895.
 *PERSIFOR FRAZER. Died April 7, 1909.
 *HOMER T. FULLER. Died August 14, 1908.
 N. J. GIROUX. Died November 30, 1890.
 *CHRISTOPHER W. HALL. Died May 10, 1911.
 *JAMES HALL. Died August 7, 1898.
 JOHN B. HATCHER. Died July 3, 1904.
 *ROBERT HAY. Died December 14, 1895.
 *ANGELO HEILPRIN. Died July 17, 1907.
 DAVID HONEYMAN. Died October 17, 1889.
 *EDWIN E. HOWELL. Died April 16, 1911.

- THOMAS STERRY HUNT. Died February 12, 1892.
- *ALPHEUS HYATT. Died January 15, 1902.
- THOMAS M. JACKSON. Died February 3, 1912.
- *JOSEPH F. JAMES. Died March 29, 1897.
- WILBUR C. KNIGHT. Died July 28, 1903.
- RALPH D. LACOE. Died February 5, 1901.
- J. C. K. LAFLAMME. Died July 6, 1910.
- DANIEL W. LANGTON. Died June 21, 1909.
- *JOSEPH LE CONTE. Died July 6, 1901.
- *J. PETER LESLEY. Died June 2, 1903.
- HENRY MCCALLEY. Died November 20, 1904.
- *W J MCGEE. Died September 4, 1912.
- OLIVER MARCY. Died March 19, 1899.
- OTHNIEL C. MARSH. Died March 18, 1899.
- JAMES E. MILLS. Died July 25, 1901.
- *HENRY B. NASON. Died January 17, 1895.
- *PETER NEFF. Died May 11, 1903.
- *JOHN S. NEWBERRY. Died December 7, 1892.
- WILLIAM H. NILES. Died September 12, 1910.
- *EDWARD ORTON. Died October 16, 1899.
- *AMOS O. OSBORN. Died March, 1911.
- *RICHARD OWEN. Died March 24, 1890.
- SAMUEL L. PENFIELD. Died August 14, 1906.
- DAVID PEARCE PENHALLOW. Died October 20, 1910.
- *FRANKLIN PLATT. Died July 24, 1900.
- WILLIAM H. PETTEE. Died May 26, 1904.
- *JOHN WESLEY POWELL. Died September 23, 1902.
- *ISRAEL C. RUSSELL. Died May 1, 1906.
- *JAMES M. SAFFORD. Died July 3, 1907.
- *CHARLES SCHAEFFER. Died November 23, 1903.
- *NATHANIEL S. SHALER. Died April 10, 1906.
- RALPH S. TARR. Died March 21, 1912.
- WILLIAM G. TIGHT. Died January 15, 1910.
- CHARLES WACHSMUTH. Died February 7, 1896.
- THOMAS C. WESTON. Died July 20, 1910.
- THEODORE G. WHITE. Died July 7, 1901.
- *GEORGE H. WILLIAMS. Died July 12, 1894.
- *ROBERT P. WHITFIELD. Died April 6, 1910.
- *J. FRANCIS WILLIAMS. Died September 9, 1891.
- *ALEXANDER WINCHELL. Died February 19, 1891.
- ALBERT A. WRIGHT. Died April 2, 1905.
- WILLIAM S. YEATES. Died February 19, 1908.

Summary

Correspondents	13
Original Fellows	48
Elected Fellows.....	319
Membership.....	380
Deceased Correspondents.....	3
Deceased Fellows.....	73

PROCEEDINGS OF THE FOURTEENTH ANNUAL MEETING
OF THE CORDILLERAN SECTION OF THE GEOLOGICAL
SOCIETY OF AMERICA, HELD AT BERKELEY, CALIFOR-
NIA, APRIL 11 AND 12, 1913.¹

GEORGE D. LOUDERBACK, *Secretary*

CONTENTS

	Page
Session of Friday, April 11.....	120
Some graphic methods for the solution of geologic problems; by W. S. Tangier Smith.....	120
Polarized skylight and the petrographic microscope; by W. S. Tangier Smith.....	120
Apparent limits of former glaciation in the northern coast ranges of California [abstract]; by R. S. Holway.....	120
Variations in rainfall in California [abstract]; by William G. Reed..	121
Coal-bearing Eocene of western Washington. I. Pierce County [abstract]; by William F. Jones.....	121
Nature of the later deformations in certain ranges of the Great Basin; by Charles L. Baker.....	122
Annual dinner.....	123
Geology of the southern end of the San Joaquin Valley [abstract]; by G. C. Gester.....	123
Session of Saturday, April 12, 1913.....	123
Physiographic features of the Haywards Rift [abstract]; by David M. Durst.....	123
Climatic provinces of the United States west of the Rockies [abstract]; by William G. Reed.....	124
Occurrence of free gold in granodiorite of Siskiyou County, California [abstract]; by A. F. Rogers and E. S. Boundey.....	124
Nomenclature of minerals [abstract]; by A. F. Rogers.....	124
Some contact metamorphic minerals in crystalline limestone at Crestmore, near Riverside, California [abstract]; by Arthur S. Eakle...	125
Election of officers.....	125
Resistant surfaces developed by erosion and deposition in the arid and semi-arid regions of Arizona; by C. F. Tolman, Jr.....	125
Occurrence of stibnite and metastibnite at Steamboat Springs, Nevada [abstract]; by J. C. Jones.....	126
Devonian of the Upper Connecticut Valley; by C. H. Hitchcock.....	126
Register of the Berkeley meeting.....	126

¹ Received by the Secretary of the Society July 23, 1913.

SESSION OF FRIDAY, APRIL 11

The Fourteenth Annual Meeting of the Cordilleran Section of the Geological Society of America was held in conjunction with the Pacific Association of Scientific Societies at the University of California, Berkeley, April 11 and 12, 1913, in room 105, Bacon Hall. In the absence of the chairman, the first meeting was called to order Friday, April 11, at 2.15 p. m., by the secretary of the section. Prof. A. C. Lawson was elected temporary chairman.

Minutes of the Thirteenth Annual Meeting were read and approved.

On motion of the secretary, it was voted to postpone the business until Saturday, and the scientific program was taken up. The following papers were presented in the order given:

SOME GRAPHIC METHODS FOR THE SOLUTION OF GEOLOGIC PROBLEMS

BY W. S. TANGIER SMITH

Read by title in the absence of the author.

POLARIZED SKYLIGHT AND THE PETROGRAPHIC MICROSCOPE

BY W. S. TANGIER SMITH

(Abstract)

This paper deals with the effects of polarized skylight in petrographic investigations and the means by which these effects may be overcome, especially by the use of a simple compensator placed before the polarizer of the microscope.

Read from manuscript and discussed by the secretary.

APPARENT LIMITS OF FORMER GLACIATION IN THE NORTHERN COAST RANGES OF CALIFORNIA

BY R. S. HOLWAY

(Abstract)

It has long been known that certain areas in the Sierra Nevada and the Klamath Mountains of California were glaciated during Pleistocene time. Glaciation in the Coast Ranges proper was first announced by the writer in 1911. The locality is Snow Mountain, 7,039 feet high, in latitude 39° 22' north and at the northwestern corner of Colusa County. Two reconnaissance trips since then seem to fix the limits of the glaciated area to favorable situations on the high peaks within a triangle roughly bounded by Snow Mountain, Black Butte in the northwest corner of Glenn County, and Hull Mountain in the

northern boundary of Lake County. The latter peaks are by checked aneroid slightly higher than Snow Mountain. The signs of glaciation included well preserved striæ on bedrock, small cirques, and moraines. The glaciated areas were small, the greatest length of any single glacier so far as found being not over 2 miles.

Presented without notes and illustrated by lantern slides. Discussion by Lawson, Turner, and Henley.

VARIATIONS IN RAINFALL IN CALIFORNIA

BY WILLIAM G. REED

(Abstract)

Wet and dry years have been recognized in California. An examination of the available records for the past 25 years shows that a wet or a dry period is not always State wide. The State may be divided on the basis of the character of the curves of seasonal precipitation and the time and duration of wet and dry periods into three sections. A northern, a central, and a southern type of rainfall variation have been made out from the preliminary study, although there is considerable irregularity at individual stations. The preliminary examination shows the necessity of a careful study of all the records in order that the limits of rainfall variation and the areas which are subject to similar variation may be determined.

Illustrated by map. Discussion by Turner and Weber.

COAL-BEARING EOCENE OF WESTERN WASHINGTON. I. PIERCE COUNTY

BY WILLIAM F. JONES

(Abstract)

INTRODUCTION

Areal extent:

General known areal extent of coal-bearing formations.

Producing areas:

1. Roslyn field.
2. King County field.
3. Pierce County field.

Previous work:

1. Willis (covering entire field), 1882-1897.
2. Washington State Geological Survey (on King County), 1912.

Development in Pierce County:

Brief description of mines.

STRATIGRAPHY

<i>Willis' division:</i>	Feet
Burnett	8,000 +
Wilkeson	1,200
Carbonado	1,300 +
	10,500 +
<i>Present division:</i>	
Burnett	8,000 +
Wilkeson	950 +
Carbonado	2,300
Melmont	1,400
Fairfax	2,000 +
	14,600 +

RELATION BETWEEN WILLIS' DIVISION AND PRESENT DIVISION OF PUGET GROUP

Basis of division:

1. Fossil flora.
2. Lithologic.
3. Coal content.

CHARACTERISTICS OF EACH DIVISION

Correlation:

1. With marine tertiary.
2. With King County field.

STRUCTURE OF PIERCE COUNTY FIELD

Major system of folding and faulting.

Submajor system of faulting.

Minor system of folding and faulting.

Subminor system of faulting.

Relation of major and minor systems.

Faulting independent of major and minor systems.

Sequence of structural development.

Illustrated by maps and sections. Discussion by Taff and Lawson.

NATURE OF THE LATER DEFORMATIONS IN CERTAIN RANGES OF THE GREAT BASIN

BY CHARLES L. BAKER

Read from manuscript by the secretary in absence of the author. Discussion by Turner, Louderback, Bain, and Lawson.

Published in Journal of Geology, volume xxi, May, 1912, pages 273-278.

An invitation to the members of the Cordilleran Section to attend an informal reception at the home of President and Mrs. Wheeler from 4.30 to 5.30 was read by the Secretary. The meeting, therefore, adjourned at 4.30.

ANNUAL DINNER

The annual dinner was held in conjunction with the Le Conte Geological Club and the Pacific Coast Section of the Paleontological Society at the Faculty Club at 7 p. m. Friday. After the dinner the question of meeting place for 1914 was discussed, as a session in the Northwest had been proposed. The meeting voted its approval of Seattle, Washington, provided the Pacific Association decided to meet there.

The following paper was then read and very generally discussed:

GEOLOGY OF THE SOUTHERN END OF THE SAN JOAQUIN VALLEY

BY G. C. GESTER

(Abstract)

The topography of this region is largely the result of an intense folding and faulting accompanied by torrential erosion, commonly found in the semi-arid regions. There is some evidence to offer that this part of the southern San Joaquin is slowly rising. Lying upon a series of granites, schists, etcetera, which are a direct continuation of similar rocks exposed in the Sierra Nevada, are a series of Tertiary sediments and volcanics. The sediments are a direct continuation of the formations exposed in the Midway Sunset district. The sedimentation becomes generally coarser toward the south and east. An extensive series of volcanics is found associated with sediments of Lower Miocene age.

Presented from notes and illustrated by a geologic map.

SESSION OF SATURDAY, APRIL 12, 1913

The meeting was called to order in room 105, Bacon Hall, at 9.45, by the temporary chairman, who, being obliged to attend a committee meeting, yielded the chair to Prof. A. S. Eakle.

The following papers were presented:

PHYSIOGRAPHIC FEATURES OF THE HAYWARDS RIFT

BY DAVID M. DURST

(Abstract)

Described the location of the rift line and the characteristic topography.

Illustrated by map. Discussion by Wilcox, Louderback, and Weber.

CLIMATIC PROVINCES OF THE UNITED STATES WEST OF THE ROCKIES

BY WILLIAM G. REED

(Abstract)

The State boundaries form an unsatisfactory method of dividing the area for climatic purposes and it can not be considered as a climatic unit. The grouping here suggested conforms more or less closely with the physiographic provinces and seems to be climatically sound. The area west of the Sierra-Cascade crest may be called the Pacific Province; it is characterized by generally mild temperatures and a winter maximum of precipitation. It may be subdivided into the Californian district with dry summers and the Oregonian district with occasional summer rains. Both districts may be further subdivided on the basis of the annual rainfall. East of the Sierra-Cascade crest is the Rain Shadow area; it is characterized by large daily and annual ranges of temperature and generally deficient precipitation. It may be subdivided into the Great Basin district with generally less than 10 inches annual rainfall; and the Snake River district with 10 to 20 inches annual rainfall, with a spring maximum.

Discussion by Weber, Louderback, and Holway.

*OCCURRENCE OF FREE GOLD IN GRANDIORITE OF SISKIYOU COUNTY,
CALIFORNIA*

BY A. F. ROGERS AND E. S. BOUNDEY

(Abstract)

An addition to the very few authentic occurrences of original gold in unaltered igneous rocks.

Illustrated by specimen.

NOMENCLATURE OF MINERALS

BY A. F. ROGERS

(Abstract)

About five thousand mineral names are in use, though there are not more than a thousand definite minerals known. It would simplify the nomenclature if names of varieties, mixtures, pseudomorphs, and isomorphous mixtures were discarded. Minerals are mainly isomorphous mixtures of simple molecules. The name of a mineral would be determined by its predominant molecule, the name being that of the end member of the isomorphous series to which it belonged. If this suggestion were adopted, such names as embolite and pisanite would be discarded, while some new names would be added.

It is recommended that mineral analyses be recorded in the form of metal and acid radicals instead of in the form of oxides, and that the molecular ratios be given with the analyses.

Presented from notes. Discussion by Eakle, Louderback, and Weber.

*SOME CONTACT METAMORPHIC MINERALS IN CRYSTALLINE LIMESTONE AT
CRESTMORE, NEAR RIVERSIDE, CALIFORNIA*

BY ARTHUR S. EAKLE

(Abstract)

An interesting deposit of white and sky blue, coarsely crystalline limestone occurs at Crestmore on a contact with granodiorite, and various minerals have been formed, some of them very unusual. The paper described xanthophyllite, monticellite, brucite, vesuvianite, garnet, wollastonite, and other silicates and contains the chemical analyses of some of them.

Illustrated by specimens.

The meeting adjourned at 12.10 for lunch.

The afternoon session was called to order at 2.25, with Professor Eakle in the chair.

ELECTION OF OFFICERS

The following officers were elected for the ensuing year:

Chairman, J. C. BRANNER.

Secretary, G. D. LOUDERBACK.

Councillor, W. S. TANGIER SMITH.

On motion of the secretary, it was voted to extend a cordial invitation to the general Society to meet in San Francisco in 1915.

It was also voted that the secretary of the section when sending preliminary notices of the annual meeting should inclose a list of members of the Cordilleran Section, which may be used as a ballot for the nomination of officers.

The following papers were then presented and discussed:

*RESISTANT SURFACES DEVELOPED BY EROSION AND DEPOSITION IN THE
ARID AND SEMI-ARID REGIONS OF ARIZONA*

BY C. F. TOLMAN, JR.

Presented from notes. Questions were asked by J. C. Jones, Holway, and Moody, bringing out further evidence for the conclusions presented. Discussion by Jones and Louderback.

OCCURRENCE OF STIBNITE AND METASTIBNITE AT STEAMBOAT SPRINGS,
NEVADA

BY J. C. JONES

(Abstract)

Antimony sulphide is at present being deposited in two forms at Steamboat Springs, Nevada: the one, stibnite, crystallizing in characteristic acicular crystals from the water in one of the pools; the other, the red amorphous metastibnite, separating with silica from the water overflowing from the pool.

An analysis of the water showed both antimony and arsenic sulphides to be in solution due to the presence of sodium sulphantimonite.

Illustrated by table of analyses and specimens. Discussion by Eakle, Louderback, and Rogers.

DEVONIAN OF THE UPPER CONNECTICUT VALLEY

BY C. H. HITCHCOCK

In the absence of the author the manuscript was read by title.

The chairman of the section being absent, Prof. C. F. Tolman, Jr., was elected to act as his substitute at the meeting of the Executive Committee of Pacific Association of Scientific Societies.

The section adjourned at 4.35 p. m., *sine die*.

REGISTER OF THE BERKELEY MEETING

FELLOWS

FRANK M. ANDERSON	GEORGE D. LOUDERBACK
HARRY FOSTER BAIN	JOHN C. MERRIAM
ARTHUR S. EAKLE	JOSEPH A. TAFF
ANDREW C. LAWSON	CYRUS F. TOLMAN
HENRY W. TURNER	

Visitors and other geologists taking part in the meeting were:

E. P. CAREY	J. O. LEWIS
D. M. DURST	W. L. MOODY
G. C. GESTER	W. G. REED
A. S. HENLEY	A. F. ROGERS
R. S. HOLWAY	C. A. WARING
J. C. JONES	A. H. WEBER
WILLIAM F. JONES	A. R. WHITMAN

G. A. WILCOX

There were also present a number of students and other visitors.

Altogether the attendance was as follows: Friday afternoon meeting, 41; Saturday morning meeting, 24; Saturday afternoon meeting, 20.

PROCEEDINGS OF THE FIFTH ANNUAL MEETING OF THE
PALEONTOLOGICAL SOCIETY, HELD AT PRINCETON,
NEW JERSEY, DECEMBER 31, 1913, AND JANUARY 1, 1914.

R. S. BASSLER, *Secretary*

CONTENTS

	Page
Session of Wednesday, December 31.....	129
Presidential address: Cambrian of western North America; by C. D. Walcott.....	130
Symposium on "The Close of the Cretaceous and Opening of Eocene Time in North America".....	130
Session of Thursday, January 1.....	130
Completion of symposium.....	130
Report of the Council.....	130
Secretary's report.....	131
Treasurer's report.....	132
Appointment of Auditing Committee.....	133
Election of officers and members.....	133
New business and announcements.....	134
Section of Invertebrate, Paleobotanic, and General Paleontology.....	135
Use of crinoid arms in studies of phylogeny [abstract]; by Elvira Wood.....	135
Western extension of some Paleozoic faunas in southeastern Missouri [abstract]; by Stuart Weller and M. G. Mehl.....	135
Mounting of rock and fossil specimens with sulphur [abstract]; by Chester A. Reeds.....	136
Restoration of Paleozoic Cephalopods; by Rudolph Ruedemann..	136
Some new paleogeographic maps of North America [abstract]; by A. W. Grabau.....	136
Devonic black shale of Michigan, Ohio, Canada, and western New York interpreted as a Paleozoic delta deposit; by A. W. Grabau.	137
Lower Paleozoic section of the Alaska-Yukon boundary [abstract]; by L. D. Burling.....	137
Cambrian brachiopoda, a study of their inclosing sediments [abstract]; by L. D. Burling.....	137
Calcareous algae from the Silurian; by Fritz Berckheimer.....	137
Cambrian and Ordovician faunas of southeastern Newfoundland [abstract]; by Gilbert Van Ingen.....	138
"Laramie" ? Puerco, and Torrejon in the San Juan Basin, New Mexico [abstract]; by William J. Sinclair.....	138
Phylogenetic development of the hexactinellid dictyosponges, as indicated by the ontogeny of an Upper Devonian species; by John M. Clarke.....	138

	Page
Minutes of the sectional meeting of Vertebrate Paleontology.....	139
Final results in the phylogeny of the Titanotheres; by H. F. Osborn.....	139
Restoration of some Pyrotherium mammals; by Frederic B. Loomis.....	139
Analysis of the Pyrotherium fauna; by Frederic B. Loomis.....	140
New methods in restoring Eotitanops and Brontotherium; by H. F. Osborn.....	140
Structure and affinities of the Multituberculata; by Robert Broom.....	140
Note on the American Triassic genus <i>Placerias</i> Lucas; by Robert Broom.....	141
Skeleton of Notharctus, an Eocene Lemuroid; by W. K. Gregory..	141
Phyletic relationships of the Lemuroidea; by W. K. Gregory....	141
Restoration of the world series of elephants and mastodons; by H. F. Osborn.....	142
Fauna of the Cumberland Pleistocene cave deposit; by J. W. Gidley.....	142
Rectigradations and alloimetrans in relation to the conception of the "Mutations" of Waagen; by H. F. Osborn.....	142
Miocene dolphin from California; by Richard S. Lull.....	142
New accessions to the exhibition series at Yale Museum; by Richard S. Lull.....	143
New mastodon find in Connecticut; by Richard S. Lull.....	143
Notes on Camarosaurus Cope; by Charles C. Mook.....	143
Relations of the American Pelycosaurs to the South African dinocephalians; by Robert Broom.....	143
Results of recent work at Rancho la Brea; by John C. Merriam..	143
Systematic position of the Mylodont sloths from Rancho la Brea; by Chester Stock.....	143
Geology of the Uinta formation; by Earl Douglass.....	144
New Titanotheres from the Uinta formation of Utah; by O. A. Peterson.....	144
Report of progress in the revision of the Lower Eocene faunas; by W. D. Matthew.....	144
Group of twenty-six associated skeletons of Leptomeryx from the White River Oligocene; by E. S. Riggs.....	145
Register of the Princeton meeting, 1913.....	145
Officers, correspondents, and members of the Paleontological Society..	146
Minutes of the Fourth Annual Meeting of the Pacific Coast Section of the Paleontological Society; by E. Dickerson, secretary.....	150
Fauna of the <i>Scutella breweriana</i> zone of the Upper Monterey series [abstract]; by B. L. Clark.....	151
Fauna of Lower Fernando series [abstract]; by Walter A. English.	151
Some West Coast Mactridæ [abstract]; by Earle Packard.....	151
Observations on the use of the percentage method in determining the age of Tertiary formations in California; by B. Martin....	152
Geological relations between the Cretaceous and Tertiary of southern California [abstract]; by Clarence A. Waring.....	152
Echinoderms of the San Pablo [abstract]; by W. S. W. Kew.....	152
Fauna of the San Pablo series [abstract]; by B. L. Clark.....	152

	Page
Terrestrial Oligocene of the Basin region and its relation to the marine Oligocene of the Pacific Coast province; by John C. Merriam.....	153
Faunal relations of the San Lorenzo Oligocene to the Eocene in California [abstract]; by Roy E. Dickerson.....	153
Vaqueros of the Santa Monica Mountains of southern California [abstract]; by Harold Hannibal.....	153
Lower Miocene of Washington [abstract]; by Charles E. Weaver.	153
Fauna of the Oligocene (?) of Oregon [abstract]; by F. M. Anderson.....	154
Faunal zones of the Martinez Eocene of California [abstract]; by Roy E. Dickerson.....	154
Comparison of the oysters of the lower and upper horizons of the Miocene of the Muir syncline [abstract]; by William V. Cruess.	154
Antelopes in the fauna of Rancho la Brea [abstract]; by Asa C. Chandler.....	155
Vertebrate fauna of the Triassic limestones at Cow Creek, Shasta County, California [abstract]; by H. C. Bryant.....	155
Some physical features of Hawver Cave; by J. C. Hawver.	155
Hawver Cave: its Pleistocene fauna [abstract]; by Chester Stock.	155
Mammalian fauna of the Pleistocene beds at Manix in the Mohave Desert region [abstract]; by John P. Buwalda.....	156
Occurrence of mammalian remains at Rancho la Brea [abstract]; by R. C. Stroner.....	156
Correlation of the Tertiary formations of the Pacific Coast and Basin regions of western United States; by J. C. Merriam.....	156
Vertebrate fauna of the Orindan and Siestan formations [abstract]; by J. C. Merriam.....	156

SESSION OF WEDNESDAY, DECEMBER 31, 1913

The Section of Vertebrate Paleontology was called to order at 10.40 a. m. in advance of the Society's first general session. This became necessary in order to allow time for the completion of the program, which had been increased at the last moment by numerous papers on vertebrate paleontology. R. S. Lull was elected chairman and W. D. Matthew secretary of the section. The minutes are printed on pages 139 to 145.

PRESIDENTIAL ADDRESS

At 2.30 p. m. a joint general session of the Geological Society of America and the Paleontological Society was held in Guyot Hall to hear the retiring address by the President of the Paleontological Society, Charles D. Walcott, who chose as his subject

CAMBRIAN OF WESTERN NORTH AMERICA

Following this address, which was illustrated by lantern slides, President Walcott called the Paleontological Society to order, and announced that on account of the general interest in the proposed symposium the business meeting usually opening the Society's sessions would be deferred until the symposium had been completed. He then introduced H. F. Osborn, who briefly outlined the purpose and scope of the symposium.

The speakers and titles of their special subjects were as follows:

SYMPOSIUM ON THE CLOSE OF THE CRETACEOUS AND OPENING OF EOCENE TIME IN NORTH AMERICA

H. F. Osborn: Introduction.

F. H. Knowlton: Paleobotanic and geologic evidence.

T. W. Stanton: Comparative geological evidence.

At 5.30 the Society adjourned for the day.

Wednesday evening the members took part in the annual dinner with the Fellows of the Geological Society of America at Procter Hall.

SESSION OF THURSDAY, JANUARY 1, 1914

Thursday morning the Society met in general session at 9.30 o'clock, with the completion of the symposium first on the program.

COMPLETION OF SYMPOSIUM

Barnum Brown: The Reptilian fauna of the Upper Cretaceous.
(Presented by H. F. Osborn.)

William J. Sinclair: Geologic and Paleontologic evidence (Mammalian).

W. D. Matthew: Discussion of the fauna of the Paleocene.

Upon the completion of Doctor Matthew's paper a general discussion of the subject was held, with remarks by Messrs. Schuchert, Stanton, Knowlton, White, Lee, Broom, Osborn, and Matthew.

At 11 a. m. Vice-President Williams took the chair and called for the report of the Council as the first matter of business on the program.

REPORT OF THE COUNCIL

To the Paleontological Society in Fifth Annual Meeting assembled:

Following the adjournment of the Society on December 31, 1912, the regular annual meeting of the Council was held at New Haven, Con-

necticut, when nominations for officers for the following year were suggested, new nominations for members, and further business were considered. Since this meeting all business of the Society has been arranged, as heretofore, by correspondence. Details of administration for the Society's fifth year are presented in the following reports of officers:

SECRETARY'S REPORT

To the Council of the Paleontological Society:

Meetings.—The proceedings of the fourth annual meeting of the Society, held at New Haven, Connecticut, December 30 and 31, 1913, have been published in volume 24 of the Bulletin of the Geological Society of America, pages 99 to 132, and distributed to the members. The scientific papers of the Paleontological Society printed during the year by the Geological Society of America and distributed to the members comprise three papers on vertebrate paleontology and two on invertebrate paleontology and stratigraphy. Three other papers delivered at the fourth annual meeting have been printed or are in press in other publications. Therefore, of 42 papers presented at the Yale meeting and at the Pacific Coast Section only nine have been published. It is, therefore, believed advisable to continue the practice commenced last year of printing in the annual proceedings rather full abstracts of all papers.

The Council's proposed nominations for officers and announcement that the fifth annual meeting of the Society would occur at Princeton, New Jersey, at the invitation of the Princeton University members, were forwarded to the members on March 15, 1913.

Membership.—During the year the Society has lost by death one of its members, Prof. William M. Fontaine, who was well known for his long services as Professor of Geology at the University of Virginia, and for his paleobotanical researches on the Permian and Mesozoic rocks of eastern North America. A sketch of his life has been presented before the Geological Society and will be published as a part of their proceedings.

Two resignations have occurred during the year; three members never perfected their membership and five have been dropped for non-payment of dues. The 17 candidates elected at the fourth annual meeting have been placed on the rolls, making the present enrollment 161.

At this year's election for Fellows of the Geological Society of America, members Miss Mignon Talbot and Messrs. Gordon, Hartnagel, Reeds, and Twenhofel of the Paleontological Society were elected to Fellowship.

Pacific Coast Section.—The Secretary of the Pacific Coast Section of the Society reports that their fourth annual meeting was held April 8,

1913, in Bacon Hall, University of California, with President F. M. Anderson presiding.

The minutes of this meeting are printed on pages 150 to 156 of this Bulletin.

Respectfully submitted.

R. S. BASSLER,
Secretary.

WASHINGTON, D. C., *December 27, 1913.*

TREASURER'S REPORT

To the Council of the Paleontological Society:

The Treasurer begs to submit the following report of the finances of the Society for the fiscal year ending December 24, 1913:

RECEIPTS

Cash on hand December 21, 1912.....	\$183.78	
Dues (with arrears from 68 members).....	210.25	
		\$394.03

EXPENDITURES

Treasurer's office:

Postage	\$5.41	
Printing and stationery.....	18.50	
		\$23.91

Secretary's office:

Expenses	\$51.24	
Secretary's allowance for clerical help.....	50.00	
		101.24

Geological Society of America:

Separates from volume 24, numbers 1 and 2.....	19.85	
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Pacific Coast Section, Paleontological Society:

Secretary's expenses.....	18.20	
Dues returned (sender not a member).....	3.00	
		\$166.20

Balance on hand December 24, 1913.....	227.83	
		\$394.03

Net increase in funds.....	44.05	
Outstanding dues.....	27.00	

Respectfully submitted.

R. S. LULL,
Treasurer.

NEW HAVEN, CONNECTICUT, *December 24, 1913.*

APPOINTMENT OF AUDITING COMMITTEE

The chairman then appointed John M. Clarke and William J. Sinclair as a committee to audit the Treasurer's accounts.

ELECTION OF OFFICERS AND MEMBERS

The declaration of the vote for officers for 1914 and for members was the next matter of business and was announced by the Secretary as follows:

*OFFICERS FOR 1914**President:*

H. F. OSBORN, New York City

First Vice-President:

F. M. ANDERSON, Berkeley, Cal.

Second Vice-President:

F. B. LOOMIS, Amherst, Mass.

Third Vice-President:

ROBERT T. JACKSON, Boston, Mass.

Secretary:

R. S. BASSLER, Washington, D. C.

Treasurer:

RICHARD S. LULL, New Haven, Conn.

Editor:

CHARLES R. EASTMAN, Washington, D. C.

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FRITZ BERCKHEIMER, Department of Paleontology, Columbia University, New York City.

JOHN T. DONEGHY, JR., 963 Yale Station, New Haven, Conn.

CLARENCE E. GORDON, Massachusetts Agricultural College, Amherst, Mass.

MARJORIE O'CONNELL, Adelphi College, Brooklyn, N. Y.

EARL L. PACKARD, 1522 Grove Street, Berkeley, Cal.

CHESTER STOCK, 492 Seventh Street, San Francisco, Cal.

EDWARD L. TROXELL, Amherst College, Amherst, Mass.

CLAUDE W. UNGER, Pottsville, Pa.

FRANCIS W. VAN TUYL, Department of Paleontology, Columbia University, New York City.

CLARENCE A. WARING, Box 162, Mayfield, Cal.

NEW BUSINESS AND ANNOUNCEMENTS

The following matters of business, which had been considered previously by the Council, were now on request of the chairman placed before the Society by the Secretary:

On the nomination of John M. Clarke the Council recommended to the Society that Dr. Henry Woodward, editor of the Geological Magazine, be elected an honorary Fellow of the Society in recognition of his great services rendered to paleontologic science. It was then voted that the Secretary cast the ballot of the Society for Doctor Woodward's election.

The names of William L. Bryant, Buffalo Society of Natural History, Buffalo, New York; Thomas C. Brown, Bryn Mawr College, Bryn Mawr, Pennsylvania, and Alexander Petrunkevitch, Yale University, New Haven, Connecticut, were not considered by the Council for membership until too late to be placed on the printed ballot. The Council, believing that it would be unjust to cause them to wait another year before election, recommended that they be elected to membership by the members present. On motion, the election of each was made unanimous.

The Society had been requested during the year to appoint a representative on the Supervisory Board of the American Year Book. The Council considered this matter and recommended that favorable action be taken. On motion, Charles R. Eastman, editor of the Society, was elected as our representative.

Methods of increasing the value of the Proceedings of the Society to all of the members and of making them of more general interest were considered by the Council, and it was recommended that abstracts of the important paleontological articles of each year be prepared and submitted to the Society at the yearly meetings for discussion and possible publication. The members voted approval of this action, and the appointment of a committee to prepare such abstracts was left to the Council.

The proposition that a chapter dealing with the Paleontology of Man be organized in the Society, suggested to the Council during the year, was next submitted to the members. After discussion and an unseconded motion that the title of the proposed chapter be changed so as to be more comprehensive, it was voted to refer the entire subject back to the Council for report next year.

The final matter of business was the consideration of the invitation of the Pacific Coast Section to hold either a regular or extra meeting of the Society in the vicinity of San Francisco during the summer of 1915. The Council suggested that the Pacific Coast Section be empowered to call an extra meeting for this time, which suggestion was formally adopted by the members.

There being no further matters of business, the members then proceeded to the reading of papers in two sections: first, Vertebrate Paleontology and, second, Invertebrate, Paleobotanic, and General Paleontology. The minutes of the vertebrate section are given on pages 139 to 145.

SECTION OF INVERTEBRATE, PALEOBOTANIC, AND GENERAL PALEONTOLOGY

The first paper of this section was presented by the author and illustrated with lantern slides; 25 minutes. Discussed by A. W. Grabau, A. F. Foerste, R. T. Jackson, with reply by Miss Wood.

USE OF CRINOID ARMS IN STUDIES OF PHYLOGENY

BY ELVIRA WOOD

(Abstract)

It has been found, in studying the phylogeny of Paleozoic crinoids, that the few young individuals preserved are usually too far advanced in development to show stages in ontogeny which can be used for working out the phylogeny of the group to which they belong. The student is thus restricted to information to be obtained from adults. The number and arrangement of calyx plates in the species of closely related genera show so little variation that they do not give definite stages in ontogeny. A study of the arms of crinoids has shown that in some species the arm, from the proximal to the distal portion, passes through a series of stages which, taken in connection with other characters, may be used to determine the phylogeny of the group to which the species belongs. The genus *Cactocrinus* has furnished an illustration of these facts, and the phylogeny of the genus and its relation to *Teleocrinus* has been indicated as far as the material available for study will permit.

The next paper was presented by the senior author without manuscript and illustrated by charts, maps, and specimens; 15 minutes. Discussed by Charles Schuchert and John M. Clarke.

WESTERN EXTENSION OF SOME PALEOZOIC FAUNAS IN SOUTHEASTERN MISSOURI

BY STUART WELLER AND M. G. MEHL

(Abstract)

The Mississippian sediments in southern Missouri in most localities lie unconformable on formations of Ordovician age, but in Ste. Genevieve County,

in an old synclinal fold, remnants of Silurian and Devonian formations have been preserved. These formations and their faunas will be briefly described, and specimens from the Lower and Middle Devonian will be exhibited.

At 12.30 the Society adjourned for luncheon, meeting again at 2 p. m., with Dr. R. T. Jackson presiding. The papers on General and Invertebrate Paleontology were then continued, the first paper being presented by the author and illustrated with specimens and a demonstration; 10 minutes.

MOUNTING OF ROCK AND FOSSIL SPECIMENS WITH SULPHUR

BY CHESTER A. REEDS

(Abstract)

During the year sulphur has been used in mounting rocks and fossils for exhibition purposes in the American Museum of Natural History. The method consists of applying a small amount of molten sulphur to the back of the specimen and inserting a modified paper-fastener. To place the specimen on exhibition, a tablet is selected through which a hole can be bored. The shanks of the fastener are then pushed through and the protruding ends bent down. Both the liquid and the viscous states of molten sulphur have been used. Specimens varying in weight from a few ounces to more than eight pounds have been mounted in this manner and have been kept in an upright position in an exhibition case for several months without apparent change.

The following paper was presented without manuscript and illustrated with lantern slides; 15 minutes. Discussed by C. A. Reeds, with reply by the author.

RESTORATION OF PALEOZOIC CEPHALOPODS

BY RUDOLPH RUEDEMANN

On account of the shortness of time still remaining, the author combined the next two papers, presenting them without manuscript and illustrating them with charts; 20 minutes. Discussed by Charles Schuchert, L. D. Burling, R. S. Bassler, and Rudolph Ruedemann, with replies by the author.

SOME NEW PALEOGEOGRAPHIC MAPS OF NORTH AMERICA

BY A. W. GRABAU

(Abstract)

A number of paleogeographic maps of North America will be shown and the basis on which they are constructed will be explained. Since they differ, as

a rule, widely from other maps published, the reasons for these differences will be considered.

DEVONIC BLACK SHALE OF MICHIGAN, OHIO, CANADA, AND WESTERN NEW YORK INTERPRETED AS A PALEOZOIC DELTA DEPOSIT

BY A. W. GRABAU

The author presented the next two papers without manuscript and illustrated them by lantern slides; 20 minutes. Discussed by Charles Schuchert, Rudolph Ruedemann, and R. S. Bassler, with reply by the author.

LOWER PALEOZOIC SECTION OF THE ALASKA-YUKON BOUNDARY

BY L. D. BURLING

(Abstract)

The section will be illustrated by photographs and vertical sections, with notes as to the character of the paleontological material collected and its relation to the systematic boundaries, the sedimentation in the district, and the correlation of the different sections.

CAMBRIAN BRACHIOPODA, A STUDY OF THEIR INCLOSING SEDIMENTS

BY L. D. BURLING

(Abstract)

A careful study of the 579 known species and varieties of Cambrian and related Ordovician Brachiopoda shows: (1) That from about 72 per cent of the localities represented in the United States National Museum brachiopods have been identified; (2) that, dividing the sediments into three groups (shale, sandstone, and limestone), 40 per cent of the genera and subgenera and 74 per cent of the species and varieties appear to have been identified from but one type of sediment; (3) that 44 per cent of the species occurring in more than one type of sediment have been identified from more than one of the three main divisions of the Cambrian, and (4) that after dividing the nearly 1,400 localities into three entirely distinct and unrelated groups there are obtained for each of the groups and for each of the types of sediment average figures which bear striking mathematical evidence of the reliability of their indication that the number of species per locality, while remarkably uniform, is smaller in shale than in sandstone, and greatest in limestone.

The final paper of the program presented by the author was illustrated by specimens and drawings; 10 minutes.

CALCAREOUS ALGÆ FROM THE SILURIAN

BY FRITZ BERCKHEIMER

The remaining papers, in the absence of their authors, were read by title.

CAMBRIAN AND ORDOVICIAN FAUNAS OF SOUTHEASTERN NEWFOUNDLAND

BY GILBERT VAN INGEN

(Abstract)

Cambrian and Ordovician rocks aggregating some 10,000 feet in thickness are well developed in the synclinal troughs of Conception and Trinity bays, where they exist as remnants of original wide sheets infolded in the faulted and overthrust synclines of a fiord coast. The Cambrian stages characterized by *Holmia*, *Protolenus*, *Paradoxides*, and *Olenus* are succeeded by Lower Ordovician shales carrying the fauna of the Welsh Tremadoc, as indicated by the presence of *Dictyograptus*, *Shumardia*, *Parabolina*, and *Angelina*. These are overlaid by a series of water shoal, ferruginous sandstones, and sandy shales carrying a fauna of inarticulate brachiopods like those of the Armorican Grit of Normandy. A sudden change from arenaceous sediments with iron oxides to a shaly facies with iron sulphides marks the introduction of abundant graptolites of the *Didymograptus nitidus* type, together with thin-shelled Orthoceratites, indicating a depression of the region during Arenig time to permit the passage of oceanic currents. A return to shoal water bay deposits is seen in the higher arenaceous ferruginous zone, which carries Asaphid and Calymenid trilobites and Schizocranian brachiopods. The highest beds of the district are spherulitic hematites, similar to those below, and fine-grain black shales carrying Schizocrania, *Lingula leseueri*, and *Westonia*, possibly of Llandeilo age. All the Cambrian and Ordovician faunas observed in the Avalon Peninsula appear to be related to the Welsh-French facies rather than to the interior North American-Northern Scottish facies.

"LARAMIE?" PUERCO AND TORREJON IN THE SAN JUAN BASIN, NEW MEXICO

BY WILLIAM J. SINCLAIR

(Abstract)

Near Ojo Alamo, New Mexico, a continuous section through the so-called "Laramie" and the overlying Puerco and Torrejon formations is exposed. Fossils are abundant and the stratigraphic relations of the beds absolutely diagrammatic. It will be shown that dinosaurs, which are abundant in the Ojo Alamo beds ("Laramie" of the United States Geological Survey), are not found above the marked erosional unconformity which separates the Puerco clays from an underlying heavy conglomeratic sandstone with many volcanic pebbles and much fossil wood. This unconformity may be traced for many miles about the southern margin of the San Juan Basin and may represent an important time hiatus. The position of the various faunal levels of the Puerco and Torrejon will also be discussed, and measured section will be presented showing their position with reference to the unconformity below the Puerco, above which dinosaurs are not found.

PHYLOGENETIC DEVELOPMENT OF THE HEXACTINELLID DICTYOSPONGES, AS INDICATED BY THE ONTOGENY OF AN UPPER DEVONIAN SPECIES

BY JOHN M. CLARKE

At 4.30 the Society adjourned.

MINUTES OF THE SECTIONAL MEETING OF VERTEBRATE PALEONTOLOGY

W. D. MATTHEW, SECRETARY

The section was called to order at 10.40 a. m., Wednesday, December 31, with R. S. Lull as chairman. W. D. Matthew was requested by the chair to act as secretary, and the meeting proceeded to the reading of papers.

The first paper was presented by the author and illustrated with lantern slides; 15 minutes:

FINAL RESULTS IN THE PHYLOGENY OF THE TITANOTHERES

BY H. F. OSBORN

The author reviewed briefly the final phylogenetic conclusions of his monograph on this family, pointing out the numerous parallel phyla represented and the remarkable completeness of the series of stages. Exceptions were found in the break between Lower and Middle Eocene stages in the phyla and another between the Upper Eocene and Lower Oligocene.

DISCUSSION

Professor SCOTT called attention to the fact that the generic name *Menodus* used by the author was antedated by *Menodon*. Professor Osborn replied that this did not constitute preoccupation according to the ruling of the International Zoological Congress that names with the different terminals—*us* and *on*—should not be considered as identical. Professor Scott rejoined that this ruling appeared to be untenable, as it might involve an identical family name for two distinct groups, and that the ruling would probably have to be rescinded in favor of that adopted by the American Ornithologists Union.

There was then presented by the author the following paper; 15 minutes:

RESTORATION OF SOME PYROTHERIUM MAMMALS

BY FREDERIC B. LOOMIS

The author described the skeletons of four types of mammals of the *Pyrotherium* fauna—*Rhynchippus* (order *Toxodontia*), *Prosotherium* (order *Typotheria*), *Protheosodon* (order *Liptoterna*), and *Pyrotherium* (order *Pyrotheria*). He regarded the last as related to the *Proboscidea*.

DISCUSSION

Professor SCOTT remarked on the importance of Doctor Loomis's work on the *Pyrotherium* fauna and noted certain interesting features. He dissented from the author as to the position of *Pyrotherium*, but postponed giving his reasons. Professor Osborn was inclined to interpret the resemblance between *Pyro-*

therium and the Proboscidea as parallelism, and cited certain reasons for this view. Doctor Matthew suggested that in order to determine whether these resemblances were to be interpreted as due to parallelism or to affinity it would be desirable to find out to what extent they were also present in similar adaptive types in other orders of mammals, in particular *Diprotodon* and *Arsinoitherium*. The author replied that he had failed to find much resemblance in *Diprotodon*, and that he regarded *Arsinoitherium* as also related to the Proboscidea through its Hyracoid affinities.

The same speaker then presented the following paper; 20 minutes:

ANALYSIS OF THE PYROTHERIUM FAUNA

BY FREDERIC B. LOOMIS

The author analyzed the fauna according to its apparent adaptation for grazing, browsing, or other habits of life. It appeared to be in large part a grazing, to a less extent a browsing, fauna, mostly adapted to open country, little or nothing of an aquatic or river bottoms element. It indicates that the country at that epoch was not unlike its present character.

DISCUSSION

Professor Scott spoke of certain contrasts between this and the Santa Cruz fauna. The rodent fauna was much less diversified. Edentates, and especially ground-sloths, were very much scarcer. The large proportion of large mammals is a no less remarkable difference.

The next paper was presented by the author and illustrated with lantern slides; 10 minutes:

NEW METHODS IN RESTORING EOTITANOPS AND BRONTOTHERIUM

BY H. F. OSBORN

The author explained the anatomical methods used in the recent restorations of these animals by the American Museum.

There was then presented

STRUCTURE AND AFFINITIES OF THE MULTITUBERCULATA

BY ROBERT BROOM

The author reviewed briefly the principal types of this order of mammals and stated how much was known of each. The recent description of a *Ptilodus* skeleton by Mr. Gidley and of a fairly complete skull of *Polymastodon* here announced were important additions to our knowledge of the group. He described the principal features of the skull of *Polymastodon*, and stated the results of his restudy of the *Ptilodus* skeleton. He compared the *Multituber-*

culates with Marsupials and Monotremes, concluding that they were allied to the latter group, which appear to be degenerate descendants.

DISCUSSION

Mr. GIDLEY dissented from Doctor Broom's interpretation of the supposed pelvis of *Ptilodus* as a scapulocoracoid, giving reasons why he was unable to accept this view. Professor Osborn commented briefly on the importance of Doctor Broom's contribution.

The meeting then adjourned.

The earlier part of the morning of Thursday, January 1, having been occupied by a general session of the Society, the Vertebrate section was called to order by Professor Lull at 11.40 a. m. and the program of papers continued as follows:

NOTE ON THE AMERICAN TRIASSIC GENUS *PLACERIAS* LUCAS

BY ROBERT BROOM

The author regards this humerus as undoubtedly *Anomodont* and with much probability belonging to a species of *Dicynodon*. It is doubtfully distinguishable from *D. (Kannemeyeria) simocephalus* Weithofer of the Upper Trias of South Africa.

SKELETON OF *NOTHARCTUS*, AN EOCENE LEMUROID

BY W. K. GREGORY

The author exhibited photographs of the skull and principal parts of the skeleton in comparison with the corresponding parts of the modern Lemur, pointing out the fundamental resemblances between them and interpreting the differences as mostly due to progressive or divergent specializations in the modern type.

PHYLETIC RELATIONSHIPS OF THE LEMUROIDEA

BY W. K. GREGORY

The author exhibited on the screen a series of photographs of skulls of the principal genera of modern Lemuroidea, pointing out the affinities and structural evolutionary stages in the several groups.

DISCUSSION

Professor OSBORN called attention to the importance of these researches, which are fundamental to a satisfactory understanding of the affinities and evolution of the whole order of Primates. Doctor Matthew inquired as to the

interpretation of the enlarged rodent-like teeth of *Cheiromys* (*Daubentonia*). The author replied that the lower pair were regarded as canines, the upper pair as incisors.

RESTORATIONS OF THE WORLD SERIES OF ELEPHANTS AND MASTODONS

BY H. F. OSBORN

The author exhibited photographs of a series of models of living and extinct Proboscideans recently executed by Mr. Charles Knight under his direction, and explained the basis of certain new features in the restorations of extinct types.

The meeting then adjourned.

The afternoon session was called to order by Professor Lull at 2.30 p. m., and the program of papers continued as follows:

FAUNA OF THE CUMBERLAND PLEISTOCENE CAVE DEPOSIT

BY J. W. GIDLEY

The author described the discovery and situation of this cave and the nature and probable origin of the deposit, and gave a brief résumé of the principal types identified in the material secured by his explorations for the National Museum.

DISCUSSION

Doctor MATTHEW commented on the interest of certain African types in this fauna and their possible interpretation as relics of a former Holarctic distribution. The author regarded this as the most plausible explanation of their occurrence. Professor Osborn also spoke of the importance of Mr. Gidley's discoveries, and especially of the positive identification of the eland.

RECTIGRADATIONS AND ALLOIMETRONS IN RELATION TO THE CONCEPTION OF THE "MUTATIONS" OF WAAGEN

BY H. F. OSBORN

The author explained the nature of these mutations which are the progressive changes in a phylum in passing from one species to another, having the same relation to geologic time that regional varieties have to geographic space. The mutative changes are of two kinds, either the progressive development of new and disappearance of old characters along certain predetermined lines of evolution (rectigradations) or changes in proportion of different parts (alloimetrans).

MIOCENE DOLPHIN FROM CALIFORNIA

BY RICHARD S. LULL

The authors exhibited photographs of the fossil skeleton of an extinct cetacean recently presented to the Yale Museum. It appeared to be nearly allied to the modern Dolphin, but more primitive in certain features.

NEW ACCESSIONS TO THE EXHIBITION SERIES AT YALE MUSEUM

BY RICHARD S. LULL

The speaker exhibited on the screen photographs of two notable specimens placed on exhibition in the Peabody Museum at Yale, a remarkably complete skeleton of a Cotylosaurian reptile, *Limnoscelis* from the Permian of New Mexico, together with a model described by Professor Williston and a mounted skeleton of *Equus scotti* from the Pleistocene of Texas.

NEW MASTODON FIND IN CONNECTICUT

BY RICHARD S. LULL

A remarkably complete skeleton of *Mastodon americanus* recently unearthed (on the property of the late Colonel Opoe at Farmington, Connecticut) under his direction. The skeleton is the most complete ever discovered in New England.

NOTES ON CAMAROSAURUS COPE

BY CHARLES C. MOOK

The author summarized the results of his studies on the Camarosaurus skeleton in the Cope collection and exhibited a photograph of the life-size reconstruction made many years ago under Professor Cope's direction. The skeleton is a composite representing several individuals; the reconstruction is chiefly of historic interest as the earliest attempt at restoration of the skeleton of a sauropodous Dinosaur. He called attention to the upright pose of the limbs. The genus *Camarosaurus* did not appear to be separable from *Morosaurus* Marsh, which it antedated by some two months.

RELATIONS OF THE AMERICAN PELYCOSAURS TO THE SOUTH AFRICAN
DINOCEPHALIANS

BY ROBERT BROOM

The author compared the principal characters of these two groups and concluded that they were fundamentally nearly allied, but represented divergently specialized adaptations. Both were offshoots from the main line of reptilia which led up into the primitive mammalia.

Doctor GREGORY commented on divergent views that had been entertained as to the affinities of the Pelycosaurs.

RESULTS OF RECENT WORK AT RANCHO LA BREA

BY JOHN C. MERRIAM

Read by title.

SYSTEMATIC POSITION OF THE MYLODONT SLOTHS FROM RANCHO LA BREA

BY CHESTER STOCK

The author pointed out the great amount of individual variation in the large series of skulls from this locality, which appeared to indicate that the genus

Paramylodon Brown was untenable. The skulls appeared to be all referable to a single species of the genus *Myiodon*.

DISCUSSION

Doctor MATTHEW noted the fact that the type of *Paramylodon* and of the recently described species *Myiodon garmani* Allen were both from the same quarry, and pointed out that the Santa Cruz ground sloths also showed a remarkably wide range of variation in characters comparatively constant in other groups of mammals. On the other hand, the ground sloths of the Pampean formation appeared to have their characters more fixed. Rapid evolutionary progress or the invasion of a new environment were possible causes of this wide range of individual variability.

GEOLOGY OF THE UINTA FORMATION

BY EARL DOUGLASS

Presented in abstract by Professor Osborn.

NEW TITANOTHERES FROM THE UINTA FORMATION OF UTAH

BY A. O. PETERSON

Presented in abstract by Professor Osborn.

Two new genera of Eocene Titanotheridæ were described, one of which has already well developed horns.

DISCUSSION

Doctor GREGORY inquired as to the possible identity of one of the new genera with *Diplacodon* Marsh. Professor Osborn replied that he presumed that it had been compared and found distinct.

REPORT OF PROGRESS IN THE REVISION OF THE LOWER EOCENE FAUNAS

BY W. D. MATTHEW

The author stated that the revision was based on the large collections secured by American Museum parties in charge of Mr. Granger in 1905 and 1909-1913. Detailed studies of the stratigraphy had been made by Doctor Sinclair and Mr. Granger, and careful record kept of the exact locality and level of every specimen. This made possible a more exact correlation of the different terranes and a division of the Lower Eocene into four distinct faunal zones. A fifth zone was referred to the top of the Paleocene. The systematic revision of the fauna was being conducted by Mr. Granger, Doctor Sinclair, and himself, especially with the aid of topotypes. Doctor Gregory had undertaken studies on the morphology and affinities of certain groups. The collections included many new genera and species and more complete specimens of most of these already known. Among the most interesting of the new types were two which appeared to be of South American affinities, related respectively to the armadillos and the homalodotheres. The progressive evolu-

tion of various phyla was well illustrated in the stages from the successive faunal zones.

*GROUP OF TWENTY-SIX ASSOCIATED SKELETONS OF LEPTOMERYX FROM
THE WHITE RIVER OLIGOCENE*

BY E. S. RIGGS

Read by title, with abstract by the chairman.

"This paper will describe the occurrence of this remarkable number of associated skeletons, the probable conditions of deposition, as evidenced by the position of the specimens, and the character of the including matrix. Note some undetermined points of anatomy and draw some conclusions as to the probable habits of the animal.

The meeting then adjourned.

REGISTER OF THE PRINCETON MEETING, 1913

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CORRESPONDENTS DECEASED

E. KOKEN, died November 24, 1912.

MEMBERS DECEASED

SAMUEL CALVIN, died April 17, 1911.

WILLIAM M. FONTAINE, died April 30, 1913.

ROBERT H. GORDON, died May 10, 1910.

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MINUTES OF THE FOURTH ANNUAL MEETING OF THE PACIFIC COAST
SECTION OF THE PALEONTOLOGICAL SOCIETY

ROY E. DICKERSON, *Secretary*

The fourth annual meeting of the Pacific Coast Section of the Paleontological Society of America was called to order by the President, F. M. Anderson, at 10 o'clock, April 8, 1913, in Bacon Hall, room 203, University of California. The minutes of the last business meeting were read, and it was suggested that the Secretary strike out the part designating that the next meeting be held during the spring recess of Stanford University for the reason that the present meetings were not being held at the time so designated.

A letter was read from the Committee on the Conservation of Wild Life in California. The Secretary was asked to send a representative to a meeting of the California Fish and Game Protective Association, and that the Society might be counted as a member of this association. The Secretary acted, as no meeting of the Paleontological Society was to be held before this meeting of the Fish and Game Protective Association. Mr. Bruce Martin was appointed representative for the Society. The Secretary asked for approval of this action, and after some discussion the Society unanimously voted to approve the action of the Secretary, and expressed sympathy for the movement for the prevention of the destruction of wild life of California.

On the motion of J. C. Merriam, it was voted that the Pacific Coast Association levy a sum not exceeding five dollars, and if the Paleontological Society can not furnish that amount that the Secretary be authorized to levy that amount outside the regular dues. The motion was carried.

The following officers were elected for the coming year:

President, J. C. MERRIAM.

Vice-President, ROY E. DICKERSON.

Secretary, C. A. WARING.

On the motion of J. C. Merriam, it was voted to meet next year at the place designated for the meeting of the Pacific Association of Scientific Societies, providing that the association meets in California; if not the next meeting of the Society will be held at Stanford University.

The presentation of papers was then taken up:

FAUNA OF THE SCUTELLA BREWERIANA ZONE OF THE UPPER MONTEREY
SERIES

BY B. L. CLARK

(Abstract)

About sixty species of invertebrates are known from the *Scutella breweriana* Zone. The relatively small number of recent species in this zone would appear to place it in the Lower Miocene. The fauna is quite distinct from that of the Lower San Pablo Series, found immediately above, and from that of the Lower Monterey Series, the *Agasoma graviga* Zone, below. It has, however, more species in common with that of the San Pablo than with that of the Lower Monterey. Its stratigraphic relations to the San Pablo and to the Lower Monterey is still in question.

FAUNA OF LOWER FERNANDO SERIES

BY WALTER A. ENGLISH

(Abstract)

A note on faunas collected in the eastern part of the Santa Clara Valley and San Fernando Valley, showing a characteristic faunal zone for the Lower Fernando horizon, or approximately the same age as the lower part of the Purissima of the standard Coast Range section.

SOME WEST COAST MACTRIDÆ

BY EARLE PACKARD

(Abstract)

Certain Mactrinæ are used in zonal work in the Tertiaries of the coast. The forms are not well known, for they vary greatly in general form and but few

constant characters were defined in the original descriptions. Those of the hinge teeth are the least variable of all of the characters. A nomenclature of the mactroid hinge has been proposed but not generally adopted. The dentition of *Schizotherus nuttallii* (Conrad) varies in certain minor details, but yet it is more constant than the general form of the shell. *Schizodesma abscissa* Gabb, *Mulinia densata* Conrad, and *Pseudocardium gabbi* (Remond) are important forms whose relations are imperfectly known. The first is an exceedingly variable species easily confused with *Mulinia densata* Conrad, but easily separable on hinge characters. *Mulinia densata* Conrad differs markedly from Gabb's *Mulinia densata*; *Pseudocardium gabbi* (Remond) differs in its dentition from *Mulinia densata* Conrad as known from the Coalinga field. Forms closely related to these three species should not be recognized as species or varieties unless they are based on hinge characters.

OBSERVATIONS ON THE USE OF THE PERCENTAGE METHOD IN DETERMINING
THE AGE OF TERTIARY FORMATIONS IN CALIFORNIA

BY B. MARTIN

GEOLOGICAL RELATIONS BETWEEN THE CRETACEOUS AND TERTIARY OF
SOUTHERN CALIFORNIA

BY CLARENCE A. WARING

(Abstract)

An account of the structural and faunal relations between the Chico and Martinez of the Calabasas sheet and a résumé of their relations in neighboring territories.

ECHINODERMS OF THE SAN PABLO

BY W. S. W. KEW

(Abstract)

In the Tertiary of the west coast, echinoderms are the best horizon determiners because of their limited range and their distinctive characters. The San Pablo Series in the vicinity of Mount Diablo has up to the present time shown the best known series of echinoid species. Thus far eight forms have been found in the San Pablo Series.

FAUNA OF THE SAN PABLO SERIES

BY B. L. CLARK

(Abstract)

The fauna of the San Pablo Series is distinctly Miocene as determined on the basis of the percentage method. The fauna contains about 150 species, less than 25 per cent of which are recent. Two distinct major faunal zones are recognizable everywhere; these, again, are separable into minor zones. From the Lower Major Zone of the San Pablo Series 69 species have been obtained, 41 of which have not been found in the Upper Major Zone. Two minor faunal zones have been recognized in the Lower Major Faunal Zone everywhere that the San Pablo is found. These two minor zones are largely based on the

echinoderms. The Lower Minor Zone is known as the *Scutella gabbi* zone. The zone above this will be known as the *Astrodapsis tumidus*, n. var., Zone. The faunas of these two minor zones are very similar outside of the echinoderms.

The Upper Major Faunal Zone is quite distinct from the Lower Major Zone; not only are the echinoderms different, but a large percentage of the species found in this zone have not been found in the lower. Ninety-one species have been obtained from this zone, 63 species of which are not found in the Lower Major Zone. This Upper Faunal Zone is also divisible into minor faunal zones. At least three of these minor faunal zones are recognizable. Here, again, the most characteristic species of each zone are the echinoderms.

The fauna from the lower part of the Upper San Pablo Series (the Upper Major Faunal Zone) is to be correlated with the Santa Margarita of Salinas Valley and Coalinga. No fauna from the southern part of the State or any other region has as yet been recognized with certainty as equivalent to the fauna of the Lower Major Zone of the San Pablo Series.

TERRESTRIAL OLIGOCENE OF THE BASIN REGION AND ITS RELATION TO
THE MARINE OLIGOCENE OF THE PACIFIC COAST PROVINCE

BY J. C. MERRIAM

FAUNAL RELATIONS OF THE SAN LORENZO OLIGOCENE TO THE EOCENE IN
CALIFORNIA

BY ROY E. DICKERSON

(Abstract)

Three species found in the San Lorenzo formation are identical with Tejon forms, and five appear to be closely related to Eocene species. The evidence confirms Arnold's determination of the age of this formation as Oligocene.

VAQUEROS OF THE SANTA MONICA MOUNTAINS OF SOUTHERN CALIFORNIA

BY HAROLD HANNIBAL

(Abstract)

Fauna, stratigraphic relations to adjacent Monterey and Tejon, lithological characters, relations to Sespe formation of Santa Clara River. General résumé of the faunal and stratigraphic relations of the Vaqueros formation of California.

LOWER MIOCENE OF WASHINGTON

BY CHARLES E. WEAVER

(Abstract)

The marine Tertiary of western Washington consists of three distinct units, each of which possesses a distinctive fauna and a lithologic character peculiar to itself. They are separated from one another by well marked unconformities. These formations are Tejon, Lower Miocene, and Upper Miocene. These broad generalizations apply to all portions of the western part of the State.

The Lower Miocene, on a stratigraphical basis, can not be subdivided. It consists of sandstones and shales, which, when traced, areally grade into one

another. The faunas do vary somewhat from top to bottom of the entire series, but the variation depends on shallow or deep water deposits. The presence of the genus *Aturia* has been used as an indicator of the Oligocene at Astoria, but recent investigations show its occurrence throughout the entire Lower Miocene series. It would be difficult to apply the term Oligocene to any part of the Lower Miocene in Washington, and, using the same criteria, not apply it to the Lower Miocene series, including everything below the distinctively Upper Miocene, which here roughly is to be correlated with the San Pablo.

FAUNA OF THE OLIGOCENE (?) OF OREGON

BY F. M. ANDERSON

(Abstract)

An account of the stratigraphic and faunal relations of the Middle Tertiary at Pittsburg and Astoria, Oregon. The beds are conformable and Lower Miocene in age.

DISCUSSION

Mr. HANNIBAL stated that an unconformity exists at Astoria, and that the Sooke beds, which are equivalent to or younger than the Astoria shales, contain no living species and are Oligocene in age.

Mr. ANDERSON stated in reply that he had studied the beds at Astoria, but no difference in dip or strike can be found.

FAUNAL ZONES OF THE MARTINEZ EOCENE OF CALIFORNIA

BY ROY E. DICKERSON

(Abstract)

Three major faunal zones are recognized in the Martinez Group. The lowermost of these zones is characteristically developed in the Martinez area, 4 miles north of Mount Diablo, in the basal beds of this group. A middle zone is well developed in this area, as well as at the type locality. This middle zone is characterized by *Trochocyathus zitteli* (Merriam) and several other species, which do not range downward to the basal portions nor upward in the *Solen stantoni* or uppermost zone. The uppermost zone is marked by the abundance of *Solen stantoni* Weaver, by the absence of many species of the *Trochocyathus zitteli* zone, and by the presence of a few species which do not occur in the middle or basal portions of this group.

COMPARISON OF THE OYSTERS OF THE LOWER AND UPPER HORIZONS OF
THE MIOCENE OF THE MUIR SYNCLINE

BY WILLIAM V. CRUESS

(Abstract)

The large Miocene oysters have been called *Ostrea titan* indiscriminately, principally on external appearance. A careful study of the muscle impressions and the ligamental pits indicate that two or three species are present in the beds of the Monterey series at Muir Station, California.

ANTELOPES IN THE FAUNA OF RANCHO LA BREA

BY ASA C. CHANDLER

(Abstract)

One of the most interesting animals found at Rancho la Brea is a diminutive antelope closely related to the living *Antilocapra* and described by W. P. Taylor in 1911 as *Capromeryx minor*. In general structure it is remarkably similar to its modern relative, differing only in minor details of the teeth and proportions of the bones. Its points of difference are reminiscent of *Hmyoceros* and *Merycodus*, and, though probably not in the direct line of descent, bridges the gap between the old and the modern. This animal is especially remarkable for its tiny size, the adult being little over half the size of our pronghorn, and some of the immature specimens being no larger than good-sized jack rabbits. It is not at all certain whether the male of the species possessed horns, but the evidence at hand shows that the female, at least, was hornless. To find such a delicate, defenseless miniature of an antelope living in the midst of the many monstrous, grotesque, and terrible animals of the North American Pleistocene is but another of the wonders revealed by the asphaltum of Rancho la Brea.

Remains of the pronghorn, *Antilocapra*, seem also to be in the fauna of Rancho la Brea.

VERTEBRATE FAUNA OF THE TRIASSIC LIMESTONES AT COW CREEK,

SHASTA COUNTY, CALIFORNIA

BY H. C. BRYANT

(Abstract)

Large exposures of Hosselkus limestone of Upper Triassic age in Shasta County have yielded a number of saurian forms (*Thallatasauria*, *Ichthysauria*) known to be characteristic of this age, and, in addition, some teeth of a cestraciont fish (*Strophodus* sp.), hitherto unknown in America. The abundant and well preserved specimens of these beds furnish important evidence as to the faunal characteristics of the Upper Triassic in California.

SOME PHYSICAL FEATURES OF HAWVER CAVE

BY J. C. HAWVER

HAWVER CAVE: ITS PLEISTOCENE FAUNA

BY CHESTER STOCK

(Abstract)

Hawver Cave occurs in a limestone lens (Calaveras formation) 5 miles east of Auburn, California. The exploration and assembling of its fauna was first accomplished by Dr. J. C. Hawver, of Auburn. Faunally it is more closely related to the Potter Creek Cave than to the Samwel Cave. It represents a later part of the middle phase of the Pleistocene.

*MAMMALIAN FAUNA OF THE PLEISTOCENE BEDS AT MANIX, IN THE
MOHAVE DESERT REGION*

BY JOHN P. BUWALDA

(Abstract)

A list of the mammalian forms represented in the collections obtained from the lacustrine deposits at Manix, in the eastern Mohave desert region. A statement of the age of the fauna and its import in establishing the date of the latest deformation of that region.

OCCURRENCE OF MAMMALIAN REMAINS AT RANCHO LA BREA

BY R. C. STRONER

(Abstract)

In the recent excavations at Rancho la Brea it is clear that the bones occur in rather deep, narrow pits; that during the accumulation of these deposits the different tar pools commonly remained distinct, due to the slow exudation of the tar; that the pockets represent a gradual accumulation built up along with the surrounding Pleistocene deposits. It is further shown that a number of the pockets contained several tons of bones massed together representing thousands of individuals and scores of species. Since the bones are found only in connection with the tar pools, it is evident that their accumulation and preservation was due to the presence of the tar.

*CORRELATION OF THE TERTIARY FORMATIONS OF THE PACIFIC COAST AND
BASIN REGIONS OF WESTERN UNITED STATES*

BY J. C. MERRIAM

VERTEBRATE FAUNA OF THE ORINDAN AND SIESTAN FORMATIONS

BY J. C. MERRIAM

(Abstract)

The Orindan and Siestan formations occurring in the hills immediately to the east of Berkeley form the larger part of a thick accumulation of fresh-water and alluvial beds resting unconformably on the marine Miocene. The Orindan formation is the lower portion of these beds, and comprises a great thickness of clays, shales, sands, conglomerates, and tuffs, with occasional beds of limestone. The Orindan is followed by a series of igneous rocks consisting mainly of andesite and basalt. The Siestan rests on the lavas covering the Orindan, and is in turn covered by a volcanic series made up largely of basalt.

The section from the base of the Orindan to the top of the lavas above the Siestan contains no marine fossils. It shows scattered through it a few remains of fresh-water mollusca and crustacea, land mollusca, land plants, and land or fresh-water vertebrates. The accumulation as a whole is evidently the result of deposition in a basin which was at times occupied, at least in part, by fresh water, and at other times may have received purely alluvial deposits.

The mammalian remains known from both the Orindan and Siestan up to the present time all represent forms such as might be expected in the late Miocene or in the earliest Pliocene; but it will be necessary both to have better material from the Orindan and Siestan and to have well known faunas of western Miocene and Pliocene for comparison before the last word on the age determination can be pronounced.

PIONEERS IN GULF COASTAL PLAIN GEOLOGY

PRESIDENTIAL ADDRESS BY EUGENE ALLEN SMITH

(Read before the Society December 30, 1913)

CONTENTS

	Page
Introductory.....	157
Early writers.....	158
American Geological Society.....	160
Early geological surveys.....	160
Work of T. A. Conrad, Isaac Lea, and Angelo Heilprin.....	161
Researches of G. W. Featherstonhaugh.....	163
Lyell's visits.....	163
Later geological surveys and studies.....	164
Texas.....	164
Arkansas.....	166
Tennessee.....	167
South Carolina and Alabama.....	168
Mississippi and Louisiana.....	170
Georgia.....	173
Florida.....	174
Cotton Culture Reports of the Tenth Census.....	176
Researches of W J McGee.....	177

INTRODUCTORY

When attending the summer meetings of the American Association for the Advancement of Science during the past three or four decades, I have been impressed by the fact that the majority of the papers read before Section E were concerned with the phenomena of the glacial drift. The reason for this is not far to seek, since the drift is the surface formation nearly everywhere present in the northern part of the country, and the question of its origin and the relations of its different phases make it a never-to-be-exhausted subject for the exercise of the imagination and ingenuity of the investigator.

I have also been impressed by the results and conclusions of the different geologists as illustrating how doctors disagree.

¹ Received by the Secretary of the Society January 17, 1914.

So in our Southern Coastal Plain we have in the Grand Gulf and Lafayette two formations occupying the greater part of its surface, about which *our* doctors disagree. As regards especially the Lafayette and its origin, some demand a submergence of the coast and a marine deposit; others an elevation and overwash deposit. We have even a denial of the very existence of such a formation by some, who say, like the immortal Betsy Prigg to Sairy Gamp concerning Mrs. Harris, "I don't believe there's no such person."

This condition of things illustrates the great difficulty in the way of a definite classification of incoherent sediments devoid of fossils, and should make clear the importance of much additional field study before official sanction shall be given to any one of the conflicting views now held by competent observers.

In selecting a subject for discussion in this address, I have thought it appropriate to give an outline of the pioneer work on the geology of the Southern States as a suitable background for a more detailed account of that part of the field with which I am most familiar, namely, the Gulf Coastal Plain, or Mississippi Embayment, as it has most appropriately been named by Doctor Hilgard.

It is obvious, by reasons of the limitations of time and the proprieties of the occasion, that this outline can not be presented in anything like completeness, and that attention must be confined mainly to a few geologists who have been the first to state clearly the problems involved and who have prepared the ground for those who have since occupied the field.

Accordingly I shall speak in more or less detail of the work of Safford in Tennessee, of Tuomey in South Carolina and Alabama, of Hopkins in Louisiana, of Hilgard in Mississippi and Louisiana, of Roemer and Hill in Texas, of T. A. Conrad and Angelo Heilprin in several states, and of McGee in the whole area of the Coastal Plain, while I must pass over with mere mention the many who have taken up the work where these pioneers left off and who have themselves made most important contributions to our science.

EARLY WRITERS

Prior to the beginning of the nineteenth century and during its first decade writers on the geology of the Southern States were comparatively few in number.

What is commonly regarded as the first work on American geology is Johann David Schoepf's "*Beitraege zur Mineralogischen Kenntniss des Oestlichen Theils von Nord Amerika und seiner Gebirge*," published in 1787.

Schoepf's examinations extended through the Eastern States and as far south as Florida, and he noted the close similarity of the Coastal Plain lands and the occurrence of waterfalls on all the rivers at the boundary between the Coastal Plain and the hilly region to the northwest, thus recognizing the "fall line" as a physiographic feature of the American Continent.²

The travels of William Bartram, of Philadelphia, through Virginia, North and South Carolina, Georgia, east and west Florida, the Cherokee country, the extensive territory of the Creek confederacy and the country of the Choctaws, published in 1791, contain, among other things, an account of the geology, soils, and natural productions of this region, although mainly devoted to observations on the flora and on the manners of the Indians.

In an article entitled "The origin of the national scientific and educational institutions in the United States," by G. Brown Goode,³ reference is made to the scientific activities of Washington during his presidency (1789-1797). On page 63 Mr. Goode says:

"He sent out with his own hand, while President, a circular letter to the best informed farmers in New York, New Jersey, Pennsylvania, Maryland, and Virginia, and having received a considerable number of answers, prepared a report on the resources of the Middle Atlantic States, which was the first of its kind written in America, and was a worthy beginning of the great library of agricultural science which has since emanated from our Government press."

Doctor Merrill, in his "Contributions to American Geology,"⁴ tells us that Thomas Jefferson, when he came to Philadelphia to be inaugurated Vice-President in 1797, brought with him a collection of fossil bones from the western part of Virginia and the manuscript on them, which he read before the American Philosophical Society, of which he had been elected president the preceding year. The paper was published in 1799 in volume IV of the "Transactions of the Society."

Baron Alexander von Humboldt, in the employ of the Spanish government, spent the years 1799 to 1804 in that part of Mexico adjacent to what is now Texas, and in his book, with map, "Journey to the Equinoctial Regions of the New Continent," may be found,⁵ "Valuable, though indirect, contributions to our knowledge of Texas, which he did not visit personally."

According to Doctor Merrill,⁶ "the year 1809 must ever be notable in the history of American geology, since it brought forth Maclure's 'Obser-

² Merrill: Contributions to the History of American Geology, p. 208.

³ American Historical Association Report, 1899, pp. 53-161.

⁴ Page 213.

⁵ Bulletin No. 45, U. S. Geological Survey, p. 9.

⁶ Contributions to the History of American Geology, p. 217.

vations on the Geology of the United States,' with a colored map of the region east of the Mississippi.

"With the exception of Guettard's Mineralogical Map of Louisiana and Canada, published in 1752, it was the earliest attempt of a geological map of America."

During the second decade of the nineteenth century important additions to our knowledge of the geology of Virginia, Tennessee, and Alabama were made by Parker Cleaveland, F. W. Gilmer, and the Rev. Elias Cornelius. The map accompanying Cleaveland's Treatise on Mineralogy and Geology was practically the Maclure map, with a few changes.

AMERICAN GEOLOGICAL SOCIETY

In 1819 the American Geological Society was organized at Yale College, with William Maclure president, and among the members many men who were afterwards important contributors to the geology of the Southern States, such as Emmons, Troost, Morton, Lea, and Vanuxem.

Merrill states that "this Society, though continuing only to 1828, and publishing nothing and leaving little that is tangible to tell of its existence, was nevertheless productive of much good in stimulating workers throughout the country and leading to the organization of a number of state geological surveys during the decade 1820-1829."⁷

EARLY GEOLOGICAL SURVEYS

With the organization of these state surveys the systematic study of the geology of the Southern States really began, and it is worthy of record that in very many cases the state universities were the pioneers in this work and their professors the first state geologists.

North Carolina was probably the first state to organize a geological survey, which was done in 1823, with an appropriation of \$250 a year for four years, Denison Olmsted, of the State University, being State Geologist. Worthy successors to Olmsted in this important position were Elisha Mitchell, Ebenezer Emmons, W. C. Kerr, Joseph A. Holmes, and Joseph Hyde Pratt, the present incumbent. All these except Professor Kerr and Professor Emmons were professors in the State University.

South Carolina followed closely on North Carolina in establishing a State Geological Survey in 1824, with Lardner Vanuxem as director, who was succeeded in turn by Edmund Ruffin, Michael Tuomey, Oscar M. Lieber, and Earl Sloan, whose term expired May 1, 1911. For the re-

⁷ Merrill: Contributions, etc., p. 239.

mainder of the year Prof. M. W. Twitchell, of the State University, was State Geologist, but after 1911 no provision was made for the continuance of the Survey.

The third decade of the nineteenth century was also an important one in the history of southern geology.

The first Geological Survey of Tennessee was authorized by the legislature in 1831 and continued until 1850, under the direction of Gerard Troost. During this time Doctor Troost made nine reports, two of which do not appear to have been published. These reports, though short, contain, according to Doctor Safford, much valuable material.⁸

WORK OF T. A. CONRAD, ISAAC LEA, AND ANGELO HEILPRIN

The year 1832 is conspicuous in the geological history of the Mississippi Embayment by reason of the beginning of a publication by Timothy A. Conrad, the "Fossil Shells of the Tertiary Formations of North America," the second and third numbers of which were devoted chiefly to descriptions of the Eocene shells of Claiborne, Alabama, with figures drawn by Mr. Conrad. The third number, published in 1835, contained a geological map of Alabama, which, so far as I know, is the first published geological map of the state. In this map the following formations are delineated: Primary, Carboniferous or Grauwacke, Bituminous Coal, Greensand, Newer Cretaceous, Eocene, and Recent.

In November, 1833, appeared Isaac Lea's "Contributions to Geology," devoted mainly to descriptions of Eocene shells from Claiborne, Alabama, collected and sent to Doctor Lea by Mr. Charles Tait, of Claiborne. Nearly all these shells were described about the same time by Conrad, as above indicated, and an unfortunate controversy as to priority arose between the two men. The duplication of the names of the Claiborne shells has naturally been a very great inconvenience to later students.

The continuation of Conrad's work in 1838 was concerned with the fossils of the Medial Tertiary, mainly along the Atlantic coast. From 1837 to 1842 Conrad was connected with the Geological Survey of New York and contributed a number of reports on the Paleozoic fossils of that state.

His subsequent work may best be spoken of here, though out of chronological order.

⁸Dr. Alfred H. Brooks, of Washington, has made the suggestion that the prominence given to agriculture in many of the earlier Geological Survey Reports is due in part at least to the fact that the states were fearful of losing much of their population by migrations to the richer lands of the Mississippi Basin.

He reported on the fossil shells collected in California by W. P. Blake in 1835; on the fossils collected by the Wilkes Expedition; the expedition of Lieutenant Lynch to the Dead Sea; the Mexican Boundary Survey, and the surveys for railroad routes to the Pacific.

In the winter of 1842 Conrad accompanied the surveying expedition of Captain Powell to Florida. Besides the Pleistocene formations of recent shells covering both the eastern and western shores of the peninsula, Conrad found at Ballast Point, Hillsborough Falls, and possibly other localities near Tampa Bay, many silicified shells which he considered as belonging to the later Eocene, and he expresses the opinion that the prevalent limestone of Florida, extending throughout the peninsula as far south at least as Tampa Bay, will be included in this division—that is, later Eocene.⁹

This prediction has been abundantly verified by later observations.

Between 1842 and 1873 Conrad was a frequent contributor to the *American Journal of Science* and to the *Proceedings of the Philadelphia Academy of Science* and to the *Journal of Conchology*. His articles, while mainly descriptive of new species of Eocene shells, yet contain many valuable stratigraphical notes. One of his latest contributions was "New Species of Fossil Shells of North Carolina," published in Professor Kerr's *Geological Report of that state* in 1875. He died in 1877.

Concerning Conrad's personality, his mode of work, and the chief events of his life, much can be learned from the *Biographical Sketch* by Dr. W. H. Dall.¹⁰

His "Contributions to the Tertiary Paleontology of the Gulf Region" probably will remain always among the most important of the publications in this field.

Angelo Heilprin was another member of the group of Philadelphia geologists who made important contributions to the knowledge of the Coastal Plain. Besides publishing between 1873 and 1891 a number of papers on the paleontology of the Tertiary formations and a memoir, entitled "Contributions to the Tertiary geology and paleontology of the United States," he published in his "Explorations on the west coast of Florida and in the Okeechobee wilderness"¹¹ the first account of the Floridian Pliocene. The value of this discovery is thoroughly recognized by all students of Coastal Plain geology.

The work thus begun by Conrad and Heilprin has been worthily con-

⁹ *Am. Jour. Sci.*, 2d series, vol. 2, 1846, p. 47.

¹⁰ *Proc. Biol. Soc. Washington*, vol. iv, pp. 112-114.

¹¹ *Wagner Free Inst. Sci.*, vol. 1, 1887.

tinued by Dr. W. H. Dall, T. H. Aldrich, and Gilbert D. Harris, but an account of these later works falls outside the scope of the present paper.

RESEARCHES OF G. W. FEATHERSTONHAUGH

In 1834-1835 G. W. Featherstonhaugh, as government geologist, made a reconnaissance of the elevated country between the Missouri and Red rivers, which embraced the Ozark region of Arkansas and extended to the present eastern border of Texas. His report (1835) on this trip has mainly a historical interest.

LYELL'S VISITS

Sir Charles Lyell's two visits to the United States gave undoubtedly a great stimulus to the study of geology in this country. On his first visit, in 1841, he went as far south as Savannah, Georgia, but on the second visit, 1845, he went west to New Orleans and thence up the Mississippi River to Memphis, Tennessee.

From every important town on his route he made side excursions by private conveyance, in this way making a fairly full reconnaissance of much of the southern country.

While in Tuscaloosa he was under the guidance of Professor Brumby, then professor of chemistry, mineralogy, and geology in the University of Alabama. Professor Brumby had already made considerable study of the geological formations about Tuscaloosa and was well qualified to point out to Mr. Lyell the most important features. It was on the occasion of an excursion into the coal regions to the northward of Tuscaloosa that the party foregathered with Mr. David Boyd, an intelligent but independent farmer, who was telling how he and his neighbors got coal by prying it up from the bottom of the river and loading it by hand into boats. Mr. Lyell contended that this was impossible, since coal was so easily eroded that its outcrop in the bed of the river would be covered by other debris. "I don't know how it is in the books," said the native, "but I'll be hanged if it aint that way in the river."

Inside the coffer dam around lock 17 on the Warrior River, I saw last summer in the rock-bottom of the river thus laid dry the outcrop of a bed of coal crossing the river just as Mr. Boyd had described it.

A method of getting coal to a market in those early days was to build a barge on the river bank near a coal outcrop, load it with coal during the summer and fall months, and when the river would rise after the winter rains the barge would be floated off and piloted down the river, sometimes as far as Mobile. But very often in going over the shoals above Tusca-

loosa, and especially over the Squaw Shoals, where there is a fall of more than 50 feet in a distance of about 5 miles, the barges were wrecked and the coal dumped into the river. Near the foot of Squaw Shoals, 25 miles above Tuscaloosa, lock 17 is now well advanced toward completion, a work which in magnitude approaches the locks of the Panama Canal. The lift of 64 feet will give deep water into the territory of the Pratt and Mary Lee seams in the Birmingham district.

To these visits of Sir Charles Lyell we are indebted for a number of exceedingly valuable papers on the geology of the Southern States. Some of the most important of these are "On the Coal Fields of Alabama,"¹² "On the Newer Deposits of the Southern States of North America,"¹³ "On the Eocene of Georgia and Alabama,"¹⁴ "On the Delta and Alluvial Deposits of the Mississippi River."¹⁵ This latter paper contains an account of the Mudlumps of the Delta and of the stump stratum of Port Hudson. "On the Relative Age of the Nummulitic Limestone of Alabama,"¹⁶ in which paper he correctly locates the Zeuglodon bed, below the Nummulitic limestone and above the Claiborne.

LATER GEOLOGICAL SURVEYS AND STUDIES

TEXAS

The travels of Bartram and of Baron von Humboldt in the territory now embraced in Texas have already been spoken of.

In 1838 the British government sent William Kennedy on a diplomatic mission to the young Republic of Texas. While there he studied closely the topography, natural history, and geology of the country, and on his return to England he published, in 1841, his "Texas" in two volumes, with carefully compiled topographic map. This work contains an account of the natural and political history of Texas and the first scientific description of the region, based on personal observation.¹⁷

In December, 1843, Dr. Ferdinand Roemer came to Texas primarily to study its adaptation to German settlement. He remained in the state until April, 1847. The results of this study appeared in two preliminary papers, published in this country under the titles "A Sketch of the Geology of Texas"¹⁸ and "Contributions to the Geology of Texas,"¹⁹ and

¹² Am. Jour. Sci., 2d series, vol. 1, 1846, pp. 371-376.

Quar. Jour. Geol. Soc., vol. II, 1846, pp. 278-282.

¹³ Quar. Jour. Geol. Soc., vol. II, 1846, pp. 405-410.

¹⁴ Am. Jour. Sci., 2d series, vol. 1, 1846, pp. 313-315.

¹⁵ Am. Jour. Sci., 2d series, vol. 3, 1847, pp. 34-39.

¹⁶ Am. Jour. Sci., 2d series, vol. 4, 1847, pp. 186-191.

¹⁷ Hill: Bulletin No. 45, U. S. Geological Survey, p. 13.

¹⁸ Am. Jour. Sci., 2d series, vol. 2, 1846, pp. 358-365.

¹⁹ Am. Jour. Sci., 2d series, vol. 6, 1848, pp. 21-28.

in two important volumes, published in Germany, with the following titles as translated: "Texas, with especial reference to German emigration and the physical condition of the country, based on personal observations, with geological map," Bonn, 1849; and "The Cretaceous Formation of Texas and its organic remains, with a description of the Tertiary and Paleozoic strata appended," Bonn, 1852.

These volumes, according to Hill,²⁰ contain the first purely scientific discussions of Texas, excelling in accuracy and fullness many of the descriptions since published; and the "Cretaceous Formation of Texas," though published in 1852, still remains the only monograph devoted entirely to the geology of the state.

Texas has also been fortunate in lying across routes surveyed by Federal expeditions, the most important of which are: First. Captain Marcy's survey of the Red River of Louisiana, the results of which were published in 1854, with reports on the geology of the route by Dr. G. G. and Dr. B. F. Shumard. Second. Maj. W. H. Emory's "Mexican Boundary Survey," published in 1857, and including papers on the geology by Schott, Hall, and Conrad. Third. "Surveys of Routes for Railroad from the Mississippi River to the Pacific," published in 1856. Two of these routes crossed parts of Texas, namely, the 35th parallel survey, conducted by Lieutenant Whipple, with Mr. Jules Marcou as geologist, and that along the 32d parallel, conducted by Capt. John Pope. Mr. Marcou wrote preliminary reports on the geology and paleontology of the 35th parallel survey, but by reason of a misunderstanding between himself and the Secretary of War the final report was written by Mr. W. P. Blake. In 1853 appeared "Sketch of a geological map of the United States," by Professor Marcou, and in 1858 his "Geology of North America," including an edition of the geological map of the United States above mentioned. It is not necessary here to speak of the controversies between Professor Marcou and a number of other geologists about some of the correlations published in this work.

The last of the Federal expeditions was conducted by Capt. John Pope, in 1857 and 1858, for the purpose of boring artesian wells on the plains. This expedition was accompanied by Dr. G. G. Shumard as geologist.

In 1886 Robert T. Hill began his studies of the geology of the Arkansas-Texas region, in connection with the United States Geological Survey and with the University of Texas, where he was for some years Professor of Geology.

As a result of this work, which occupied most of his time until 1904, a great system was added to the Cretaceous of Texas, as it was known in

²⁰ Bulletin No. 45, U. S. Geological Survey, pp. 15-18.

the time of his distinguished predecessor, Roemer, and the stratigraphy of the component formations was accurately deciphered. He extended his researches into Mexico, and we owe to him much of our knowledge of the geology of that country.

He was later associated with Alexander Agassiz in explorations of Central America and the West Indies. His publications on these countries, besides describing local geologic conditions, have an important bearing on the correlation of the Cretaceous and Tertiary formations of the Mediterranean region of the Western Hemisphere.

The following estimate of the work of Mr. Hill is given by one who is perhaps most familiar with it:

"The most important contribution of Mr. Robert T. Hill to Southern States Geology, in my opinion, is his discovery of the true sequence of the Cretaceous formations of the Texan-Arkansan region, the recognition of the Balcones fault and the relations of the physiographic features accompanying it, and the discrimination between the Upper Cretaceous (Gulf series) and the Lower Cretaceous (Comanche series). The Comanche series is considered so important by Chamberlin and Salisbury and Schuchert that they separate it from what they consider the Cretaceous proper (Upper Cretaceous), and give to each equal value as a system. His studies of river terraces were among the first careful investigations of that kind in this country. His contributions to the geology of Mexico, Panama, Costa Rica, and the West Indies were important. In fact wherever he went he made valuable additions to the fund of geologic information. He is perhaps the first reconnaissance geologist of this day. Hill possesses a synthetic mind and has been able to bring information gleaned from a variety of fields and diverse lines of research to bear on the interpretation of problems of geologic history, and has illuminated all subjects that he has handled."

It would lead us too far to speak in detail of the Texas geological surveys as conducted by Shumard, Moore, Buckley, Dumble, Phillips, and others.

ARKANSAS

Featherstonhaugh's reconnaissance of 1834 and 1835, embracing part of Arkansas, has already been referred to.

In 1857 the first Geological Survey of Arkansas was inaugurated, with Dr. David Dale Owen as State Geologist. His first report was published in 1858. Doctor Owen died in 1860. His second report, edited by his brother, Robert Dale Owen, was published in that year.

Between 1868 and 1875 several state geologists were appointed, but no reports were prepared and very little accomplished—a circumstance which may be attributed to the general demoralization of the state government during the Reconstruction period. After an interruption of twelve years

the Survey was revived. Dr. John C. Branner was appointed State Geologist, and served in this capacity to the end of the term set by the legislature, namely, 1893.

Time will not permit of more than a passing mention of the splendid reports of Doctor Branner and his colleagues and those of Prof. A. H. Purdue, his successor, who, as Professor of Geology in the State University, was by legislative act made State Geologist, *ex officio*, in 1907. So also we must pass over the excellent work of Gilbert Harris and A. C. Veatch in southern Arkansas and adjacent parts of Louisiana.

TENNESSEE

Mention has already been made of the first Geological Survey of Tennessee, 1831-1850. A second survey was authorized by the legislature of 1854 and Dr. James M. Safford was appointed State Geologist. Doctor Safford published a preliminary report in 1856. In February, 1860, it was thought desirable to publish a full report on the geology of the state so far as it was practicable to do so, and this report was begun then, but the war came on before the work had progressed very far and put a stop to it. In 1868 the legislature again authorized the preparation of the full report, which was published, with geological map and some illustrations, in 1869. Doctor Safford continued nominally as State Geologist, but without appropriations, until a few years before his death, which occurred on July 3, 1907.

In his final report Doctor Safford treats in Part I of the physical features of the state; in Part II of the geological structure and formations; in Part III of the minerals and rocks of special use, and in Part IV of the soils and agricultural features. While the Doctor states that this report is not a complete presentation of the geology of Tennessee, but rather an introduction to such a presentation, it still remains one of the best of the state reports either north or south.

Doctor Safford was one of the agents of the Tenth Census in 1880, and prepared the reports on Tennessee and Kentucky for the Cotton Culture Division directed by Doctor Hilgard.

In the reports of the United States Geological Survey covering the domain of Tennessee, one looks in vain for many of the familiar names given by Doctor Safford. The "Knox Dolomite," I believe, has survived. Now, while "a rose by any other name may smell as sweet," there is yet much in a name to recall the excellence of this early work, and I think we honor ourselves in honoring the pioneer. How much would easily be possible in this direction by a great organization with autocratic power.

A third Survey was authorized by the legislature in 1909. Dr. George

H. Ashley was appointed State Geologist, with Professors L. C. Glenn and C. H. Gordon as assistants. On the resignation of Doctor Ashley, in 1912, Prof. A. H. Purdue, of Arkansas, the present incumbent was appointed his successor.

SOUTH CAROLINA AND ALABAMA

Prof. Michael Tuomey succeeded Edmund Ruffin as State Geologist of South Carolina in 1844 and published his first report in November of the same year. His second and final report appeared in 1848. Meanwhile, in 1847, he was called to the University of Alabama as Professor of Geology, Mineralogy, and Agricultural Chemistry, with the stipulation that he should spend each year a part of his time in geological explorations in the state. In accordance with this arrangement he immediately began field studies, publishing in the newspapers of Tuscaloosa such extracts from his notes as might be of general interest. In recognition of this effort, the state legislature in January, 1848, appointed him State Geologist, without salary, and requested him to make to that body a report of his work for publication by the state. Thus was begun the first Geological Survey of Alabama.

In 1849 Professor Tuomey presented to the legislature his first report, which was published in 1850 by the state. The geological map, however, appeared later.

He continued his explorations at the expense of the University of Alabama, from 1848 to 1853. In 1854 the legislature of Alabama passed an act providing for a geological and agricultural survey of the state and appropriating funds for the salary of the State Geologist and for the expenses of the Survey. Professor Tuomey was continued as State Geologist, and, until his death in 1857, devoted his entire time to the Survey. His office was at the University of Alabama, where he occasionally delivered a course of lectures. The second report was ordered to be printed in 1856, but was not published until 1858. It included a second geological map of the state. In these two reports, with accompanying maps, the geologic subdivisions of Alabama were quite accurately defined and the future importance of the coal and iron deposits of the state clearly foretold.

Concerning Tuomey's work in South Carolina, the editor of the *American Journal of Science* in an obituary notice²¹ says: "In his survey of South Carolina he brought out many facts of prominent interest, illustrating important principles in the geology of the continent and the history of seashore deposits." The treatise of Tuomey and Holmes on the fossils of South Carolina was a work far in advance of its time.

²¹ *Am. Jour. Sci.*, 2d series, vol. 23, March 30, 1857, p. 448.

Those of us who have followed Tuomey in Alabama realize most fully the comprehensive grasp he had of the geology of the state. No one but a master of the subject could have accomplished what he did in so limited a time. His reports, after a lapse of more than fifty years, are still consulted. His successors have been mainly occupied in filling in with details the outline which he gave.

He was a man of great information, and his memory was stored with instructive facts and amusing anecdotes.

"These qualities, joined to the manners of a finished gentleman of the old school, and a manly, dignified presence, made him a most agreeable companion.

"As a teacher, Professor Tuomey possessed in a remarkable degree the faculty of interesting the student, and those even who cared little for the subject-matter of his lectures were attracted by his style and found both entertainment and instruction in his discourses. His native Irish wit did much to render his lectures entertaining, especially to those who were not the victims of it, for it must be admitted that he did not always spare the feelings of the student at whose expense he could make a good point. He was particularly unmerciful in his rebukes and exposures of shams and affectations.

"The quality which attracted the students in his lectures makes his geological reports very interesting reading. One of the elements contributing perhaps most to this interest is the impression conveyed that the author is speaking out of the fullness of his knowledge."²²

Suffering from the malady which, on the 30th of March, 1857, terminated his life, Professor Tuomey came from Mobile to Tuscaloosa by steamboat, on the arrival of which there was a great number of the citizens of Tuscaloosa assembled at the wharf to meet him. As the procession of carriages wound its way up the hill from the river, Professor Tuomey looked out of his carriage window at the long line, remarking that he was probably the first man to be a living witness of his own funeral procession.

After the death of Professor Tuomey, the Civil War and the resulting Reconstruction problems overshadowed all other subjects, and no geologic work was carried on by the state until 1873. During this interval, however, a Commissioner of Industrial Resources was one of the regular officers of the state, and four short pamphlets were issued from his office between 1869 and 1874.

In 1871 the University of Alabama, on its reorganization, again took the lead in geologic investigations by authorizing the Professor of Geology in that institution to spend a part of his time in geologic field work.

²² Eugene A. Smith: Sketch of the life of Michael Tuomey. *American Geologist*, vol. xx, 1897.

In 1873 the legislature passed an act to revive and complete the Geological and Agricultural Survey of the state, appointed Prof. Eugene A. Smith, of the University of Alabama, State Geologist, and made a small appropriation for a period of ten years for the expenses of the Survey. The State Geologist received no salary from the state during this period.

For most of this time Prof. Henry McCalley was assistant on the Survey, serving also without pay except from the University. In 1883 and again in 1891 the appropriations for the Survey were increased and salaries for State Geologist and assistants provided for. During this period, from 1873 to the present time, about forty reports and maps have been issued by the Survey.

MISSISSIPPI AND LOUISIANA

The organization of the first Mississippi Geological Survey followed close on that of Alabama, the act taking effect early in 1850. Prof. John Millington, of the University of Mississippi, was the first State Geologist, though the first report was made by his assistant, Prof. B. L. C. Wailes, afterwards State Geologist. In 1853 Wailes was succeeded by Lewis Harper. In 1855 the position of assistant to Harper was offered to Eugene W. Hilgard, then just returned from a European university (Heidelberg), and thus began the career of the most distinguished worker in Gulf Coastal Plain Geology.

It is worth recording that Doctor Hilgard accepted this position "amid the sincere condolences of his scientific friends on his assignment to so uninteresting a field, where the Paleozoic formations (then occupying almost exclusively the minds of American geologists) were unrepresented."

The fame which Hilgard has won for himself in this "uninteresting" field is known to all geologists. He has laid the foundation on which most subsequent work in the "Mississippi Embayment," as he named it, securely rests, and after the lapse of more than fifty years since the publication in 1860 of his report his work is appreciated and referred to as authoritative not only by the farmers and other citizens of that state, but by the geologists who have succeeded him.

He became State Geologist early in 1857, which position he held, at least nominally, until 1872, with the exception of a few years between 1866 and 1870, when Dr. George Little was the director.

From the beginning of his connection with the State Survey, Hilgard saw that it could never maintain itself in the public esteem on the basis of mineral discoveries alone, and that it must seek its main support in what services it might render to agriculture. He accordingly made a point of paying particular attention to the surface features—vegetation,

soils, water supply, and marls. In the prosecution of these studies the close connection between the surface vegetation and the underlying formations became so striking that he was soon largely able to avail himself of this vegetation in tracing out the limits of adjacent formations and in searching for outcrops.

In our studies of the Coastal Plain of Alabama your present speaker and his associate, Daniel W. Langdon, have time and again found that this method of geologizing is by no means to be neglected or held in slight esteem.

In the 1860 report, about evenly divided between agricultural and geology, chemical analyses of typical soils of the several agricultural regions are given, along with discussions and estimates of their cultural value as indicated by these analyses considered in connection with the native vegetation. Hilgard's later studies of these relations, carried out in the preparation of the Cotton Culture Reports of the Tenth Census, and during many years of research in California, seem to have established the right of soil analysis to be considered as an essential and often decisive factor in the estimation of the cultural value of virgin soils.

The geological half of the report presents the geology of Mississippi practically as it is known at the present day, except as to the fixing of the age of the Port Hudson beds, as below mentioned, and the investigation of the geology of the Mississippi bottom from Memphis to Yazoo City, and the tracing of the Lower Claiborne formation westward to the border of this bottom. The two latter were assigned to me and carried out in 1870 and 1871. These additions and revisions are shown on a map of Mississippi published by T. S. Hardy, state engineer, in 1872, and reproduced, with some slight changes, in the map accompanying the report of Eckel and Crider in 1907.²³

In 1867, under the auspices of the Smithsonian Institution, and in 1869, under the auspices of the New Orleans Academy of Sciences, opportunity was given to Doctor Hilgard to extend his researches down the Mississippi River to the passes and through Louisiana in a thirty-day reconnaissance trip. In these excursions the post-Pliocene age of the Port Hudson "stump stratum" and, by inference at least, its extension from the Sabine River to Mobile Bay were definitely determined, and the Coast Pliocene of the 1860 map was changed to Port Hudson. The results of these expeditions may be summarized as follows:

1. The outlining of the Mississippi Embayment in Louisiana and Mississippi.

²³ Mississippi Geological Survey, Bulletin No. 1.

2. The outline geological study and mapping of these two states.

He was the first to give a clear and definite account of the origin and distribution of the surface formation which he called Orange Sand, but which later by agreement has received the name Lafayette. While some question has arisen during the last few years as to the appropriateness of the name Lafayette, I think time will confirm Hilgard's conclusions as to the existence of a surface formation over the area of the Gulf Coastal Plain, by whatever name it be called, and as to the general mode of its accumulation.

So, also, he was the first to give a definite account of the great series of river and estuarine deposits, the Grand Gulf, representing, as he claimed, all geological time between the Vicksburg and the Lafayette, although no recognizable fossils had been observed by him.

The finding in the last few years of beds containing leaf impressions in various parts of this territory and their identification as Lower Oligocene, Upper Oligocene, Miocene, and Pliocene, respectively, appear to demonstrate the correctness of Hilgard's original conclusion, and the name Grand Gulf will probably stand or should stand not perhaps as a formation name, but as the collective name of a very definite and apparently unique type of Coastal Plain sediments, or shall I say Mississippi River sediments?

3. The recognition of the Cretaceous Ridge or backbone of Louisiana, from Lake Bistineau to the chain of Salt Islands, and the determination (inferential) of the Cretaceous age of the rock-salt and sulphur deposits of Calcasieu parish.

4. Study of the exceptional features of the Lower Mississippi delta and of the mud lumps and their origin and the definite correlation of the Port Hudson formation.

This work on the Mississippi delta mainly secured for him membership in the National Academy of Sciences.

The geology and other natural features of Louisiana have been treated incidentally by numerous authors, such as Bartram, Maclure, Conrad, and Lyell, above mentioned, and by W. M. Carpenter, 1838; C. Peck, 1851, and C. G. Forshey, 1853; but R. Thomassy's "*Geologie Pratique de la Louisiane*," 1860, with its supplement, 1863, is the first systematic treatise on the topography and geology of the state.

In March of 1869 the Louisiana State Geological and Topographic Survey was inaugurated under the auspices of the State Seminary, subsequently the Louisiana State University. The first explorations of Dr. F. V. Hopkins, geologist, followed close on Hilgard's reconnaissance, and his first report for 1869 in like manner followed close on Hilgard's pre-

liminary report of his reconnaissance, published the same year. The supplementary and final report of Hilgard's reconnaissance was published in 1872, by which time three reports had been issued by Doctor Hopkins, of the Louisiana Survey. In these Hilgard found many confirmations of his conclusions and many observations supplementary to his own.

Of the excellent work of Lerch, Clendenin, Gilbert Harris, and his associates in Louisiana geology, only bare mention can be made in this address.

Hilgard left the University of Mississippi for the University of Michigan in 1873, and after two years' service there he was called to the University of California as Professor of Agricultural Chemistry and Director of the California Experiment Station (the first to be established in the United States) and Dean of the Faculty of Instruction in Agriculture.

His continued agitation for agricultural instruction in the public schools of California and the popularization of rational agriculture, together with the broad instruction personally imparted, have given him an extraordinary popularity in that state, just as his 1860 report has done for him in Mississippi. Witness the beautiful Hilgard avenue in Berkeley.

His achievements in soil investigations, and particularly his work on arid countries and soils, which brought him a gold medal from the Munich Academy, a semi-centennial diploma from the University of Heidelberg, and a world-wide fame, while carried out mainly in California, should at least be referred to here, as they are the logical outcome of researches begun in Mississippi.

GEORGIA

During the first three decades of the last century the most important notes on the geology of Georgia are to be found in the writings of Bartram, Maclure, Cornelius, Morton, and Shepard. The first attempt at a systematic study of it was made in 1836 by the establishment of a State Geological Survey and the appointment of Mr. John R. Cotting as State Geologist. He had previously made investigations and a report on the counties of Burke and Richmond at the expense of those counties, and it was because of these reports that Governor Schley recommended to the state legislature the action above mentioned.

Mr. Cotting's first report as State Geologist was submitted to the legislature in 1837. Though recommended to be printed by the proper committee, this report was never published and the Survey was abolished in 1840.

Between 1840 and 1874 there were no official investigations of the geology of Georgia, though numerous valuable contributions thereto were made, notably by Conrad, Lyell, Couper, Marcou, Jackson, Stephenson, and Bradley.

In 1874 the Survey was revived, with an annual appropriation of \$10,000 for five years, and Dr. George Little was appointed State Geologist. Under Doctor Little two annual Reports of Progress were made, and a paper of 126 pages was published on the Geology, Water Powers, etc., of the state in the Handbook of Georgia, issued by the State Agricultural Department. A catalogue of the ores, rocks, and woods selected for the Paris Exposition was also published. This Survey was discontinued in 1879 and reorganized in 1889, with Dr. J. W. Spencer as director. Doctor Spencer published two reports, and was succeeded in 1893 by Prof. W. S. Yeates, who continued in office until his death, in 1908. His successor, Prof. S. W. McCallie, is the present incumbent. Under the direction of Professor Yeates and Professor McCallie a number of valuable reports have been published, mainly of economic character.

FLORIDA

The fascination of the "Land of Flowers" has drawn to its shores explorers and travelers from the earliest times. Witness the travels of Catesby, in 1731; of Bartram, 1807; of John Lee Williams, who has given one of the best descriptions of this region in his volumes published in 1827 and 1837, respectively. It has drawn also a host of scientific men, such as Lieut. J. H. Allen, 1846; Prof. J. W. Bailey, 1850; T. A. Conrad, 1834 and 1846; Michael Tuomey, 1850; Joseph Le Conte, 1857; all of whom have contributed valuable notes concerning the geology of the state as noted below.

Notwithstanding these early records to the contrary, the geological maps prior to 1880 concede to Florida only the more recent formations.

In my Florida Cotton Culture Report of the Tenth Census, above mentioned, it is shown that the peninsula is underlain for the greater part of its length by the equivalent of the Vicksburg limestone, over which there are in many places discontinuous deposits which at that time were classified as Miocene (since in part called Upper Oligocene). This was hailed as an important discovery, although Eocene shells had been observed and described from the vicinity of Tampa Bay by Lieutenant Allen, Professor Tuomey, Mr. Conrad, and possibly others; and Mr. Conrad had in 1842 already expressed his opinion that this Upper Eocene limestone, as he defined it in Georgia, would be found to underlie the peninsula. Our observations in 1880 furnished proof of the correctness

of this conjecture, and also necessitated the restriction to the extreme southern end of the peninsula of Professor Le Conte's theory of its growth.

Dr. George W. Hawes, of the Smithsonian Institution, who had charge of the building stones statistics for this Tenth Census, received from Alachua County, Florida, a sample of so-called building stone, which on analysis was found to contain over 16 per cent of phosphoric acid. This analysis was forwarded to me and was published in the Florida Report on Cotton Culture, volume VI, of the Tenth Census, and is, so far as I know, the first published analysis of this phosphate, since found to be extensively distributed throughout the state and now forming the basis of a great industry.

In 1884 Daniel W. Langdon, while working for the Geological Survey of Alabama, made his memorable discovery of a series of Miocene formations, as they were then called, along Chattahoochee River between Chattahoochee Landing and Alum Bluff, thus filling the gap in the knowledge of the stratigraphic sequence of the post-Vicksburg marine Tertiaries of the Gulf Coastal Plain. The third bed from the top of Langdon's section at Alum Bluff is composed of calcareous sands, which contain well preserved shells of undoubted Miocene age (according to the present nomenclature). This bed overlies other fossiliferous sands, which Langdon also considered Miocene, but which are now classed by Dall as Upper Oligocene. The lowest member of the Appalachicola River section, a white argillaceous limestone, somewhat resembling the Vicksburg, which, however, it overlies, is seen at Chattahoochee Landing and at several points farther down the river, where it passes below the basal bed of the Alum Bluff section.

In contrast to the highly fossiliferous sandy marls exposed at Alum Bluff, this limestone contains relatively few fossils; but a sufficient number and variety have been obtained to establish its essential equivalence with the fossiliferous limestone of the Tampa formation at Tampa, Florida. Langdon was correct in considering it a part of the Miocene, as the period name was then applied. For this limestone formation overlying the Vicksburg he proposed the name *Chattahoochee*.

Later investigations have definitely fixed its age and at the same time have led to some changes in the nomenclature, the Vicksburg being now classed as Lower Oligocene, the Chattahoochee and the lower beds exposed at Alum Bluff = (Alum Bluff formation) as Upper Oligocene, while of the beds exposed at the bluff only some of the upper retain the name of Miocene (Chesapeake) = (Choctawhatchee formation).

It is only fair to state that the paleontologists are not yet all agreed as to the necessity for these changes.

In spite of the widespread interest in Florida, no definite State Geological Survey was provided for until 1886, when Dr. J. Kost was appointed State Geologist. He published his first report early in 1887, but the appropriation lapsed after that year. After an interval of 20 years the present Geological Survey was organized in 1907, with Prof. E. H. Sellards as State Geologist. Under his direction the work has been vigorously prosecuted, and a number of valuable reports, mostly of an economic character, have been published. In much of this work Doctor Sellards has had the active cooperation of the United States Geological Survey.

COTTON CULTURE REPORTS OF THE TENTH CENSUS.

Probably no work has done more for the correlation of the scattered accounts of the geology of the Southern States than the Cotton Culture Reports of the Tenth Census (1880), prepared under the direction of Doctor Hilgard, with the enlightened support of Gen. Francis A. Walker, Superintendent of the Census. Besides having general direction of the whole and preparing the general discussions of cotton production in the United States, including soil investigations, the cotton-seed industries, and measurements of cotton fibers, Doctor Hilgard wrote the special descriptions of Mississippi, Louisiana, and California. Georgia, Texas, Arkansas, Indian Territory, and Missouri were written up by Dr. R. H. Loughridge; Tennessee and Kentucky, by Dr. J. M. Safford; North Carolina and Virginia, by Prof. W. C. Kerr; South Carolina, by Mr. Harry Hammond, and Alabama and Florida, by Eugene A. Smith.

In these reports a summary of the physical and geological features of each state is first given. Then follow accounts of the agricultural features and capabilities of the Cotton States, such as should be of interest to immigrants and investors, along with special descriptions of each county, with soil maps and maps showing the relation between the area cultivated in cotton and the total area of each state. In the Mississippi and Louisiana reports Doctor Hilgard included many soil analyses made in the laboratory of the University of Mississippi after the publication of the 1860 report. Many new analyses of soils from all the states concerned were carried out in the laboratory of the University of Alabama, under the direction of Doctor Loughridge and myself, and altogether the reports are reliable handbooks of the Cotton States as regards general and agricultural information, and deserve to be far more widely known than they are.

In a recent letter Doctor Hilgard comments on these reports as follows: "The Census Cotton Report, for all the hard work it cost, has found little appreciation because of the medium of publication, quarto at

that. Don't let us do it again." But all was not lost in the quarto volumes, for in Alabama and South Carolina at least the Cotton Culture Reports were republished as State Geological Survey Reports, and have been very thoroughly appreciated and have furnished the meat for numerous subsequent handbooks.

Personally, Doctor Hilgard is one of the most lovable of men. His extraordinary fund of general as well as of special information, along with his cheerfulness and vivacity, notwithstanding the handicap of a rather frail constitution, make him a delightful companion, and his letters, even on technical or scientific matters, are always enlivened by humorous and witty remarks, so that they are truly good reading.

Although he came to America as a young man, he is master of the English language, as his numerous writings will show, and in his spoken word there is practically nothing of the foreign accent, although there is a slight lisp which might perhaps be mistaken for it. In German, of course, and in French and Spanish he appears equally at home and fluent. Meeting with him in 1891 after a lapse of 20 years, I could see no signs of advancing age, no gray hairs. Only a few months ago in a letter he says, "Don't forget to come out this way whenever you can—I may live a while yet, despite accidents," referring to a fall from a step-ladder sustained by him a year ago, which resulted in quite a serious shock and the fracture of a bone. May he live long and prosper.

RESEARCHES OF W J MCGEE

This sketch would by no means be complete without special mention of the great work of W J McGee on the Lafayette formation. McGee's early work was on the glacial formations of his native state, Iowa, but later, as the Chief Assistant of Major Powell, Director of the United States Geological Survey, his studies extended to the formations about Washington, Chesapeake Bay, Potomac River, and thence down the Atlantic Coastal Plain and westward to the Mississippi Embayment.

The Pleistocene formations in this territory he named Columbia and described in much detail. The Atlantic Coast equivalent of Hilgard's "Orange Sand" he called "Appomattox." Since by the rulings of the United States Geological Survey the use of descriptive names for formations was tabooed, he was generous enough to agree to leave to Doctor Hilgard the selection of another name for the formation which would pass muster at headquarters. After a conference between McGee, Hilgard, Le Conte, and Loughridge, the name Lafayette was accepted, the type locality being the exposures in Lafayette County, Mississippi, in the eastern part of which many characteristic occurrences of the "red sand" and

pebbles are to be found overlying the Eocene everywhere, capping the hilltops, and unconformable to the Eocene in every case. At the Lunch Club of the United States Geological Survey, McGee was the subject of a good deal of good-natured chaffing for having surrendered his name "Appomattox." Clearly, Doctor Hilgard was entitled to consideration in this matter of renaming the formation, but how many would have had the unselfishness to do the right thing at the sacrifice of a little personal credit?

Although McGee's work on the Lafayette belongs to the modern time, it may not be passed over even in a fragmentary sketch like this. While we may not all agree with his conclusions as to the mode of origin of the Lafayette, and while some things foreign have been included by him in his Lafayette, yet his treatise in the Twelfth Annual Report of the Director of the United States Geological Survey will always stand as one of the classics of American geology.

GEOLOGICAL SECTION ALONG THE YUKON-ALASKA BOUNDARY LINE BETWEEN YUKON AND PORCUPINE RIVERS¹

BY D. D. CAIRNES

(Presented before the Society December 28, 1912)

CONTENTS

	Page
Introduction.....	179
Previous work.....	180
Topography.....	180
General geology.....	182
General statement.....	182
Table of formations.....	184
Metamorphic rocks.....	184
Pre-Cambrian (?)—Yukon group.....	184
Dominantly sedimentary rocks.....	187
Lower Cambrian or pre-Cambrian—Tindir group.....	187
Devono-Cambrian limestones and dolomites.....	190
Devono-Ordovician shale—chert series.....	195
Carboniferous.....	196
General.....	196
Shale series.....	196
Racquet group.....	197
Nation River formation.....	199
Permo-Carboniferous (?) conglomerate.....	199
Mesozoic-Pennsylvanian—Orange group.....	201
Quaternary—superficial deposits.....	202
Igneous rocks.....	203
Summary and conclusions.....	203

INTRODUCTION

During the field seasons of 1911 and 1912, the writer was employed mapping and studying the geology along the 141st meridian (the Yukon-Alaska International Boundary) between Porcupine and Yukon rivers, or between latitudes $67^{\circ} 25'$ and $64^{\circ} 40'$, a distance of 191 miles. This work

¹ Manuscript received by the Secretary of the Geological Society of America November 18, 1913.

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was performed on behalf of the Canadian Geological Survey, and was extended for 2 or 3 miles on each side of the boundary line, an agreement having been entered into between the Geological Surveys of the United States and Canada whereby geological work was conducted on both sides of the 141st meridian to the north of the Porcupine, by members of the United States Survey, in exchange for similar work by the Canadian Geological Survey, to the south of this river.

The belt to the south of Porcupine River proved to be of particular interest and stratigraphic importance, as all the Paleozoic systems from the Cambrian to the Carboniferous are represented, and nowhere else in the entire Rocky Mountain region of Canada and the United States is so complete a section of the Paleozoic known within so limited an area. A considerable collection of fossils was obtained, which includes, in addition to the Cambrian faunas, many other interesting varieties, including graptolites, which are of rare occurrence in Alaska and Yukon.

PREVIOUS WORK

No geological work has been performed along the 141st meridian between the Porcupine and the Yukon except in the immediate vicinity of these rivers. McConnell came down Porcupine River in 1888, making a geological reconnaissance en route,² and Kindle made a geological examination of the rock formations along the Porcupine below New Rampart House for the United States Geological Survey during the summer of 1907.³ In addition a number of geologists, including McConnell,⁴ Spurr,⁵ Prindle,⁶ Brooks and Kindle,⁷ and others have reported on the geological formations along Yukon River in the vicinity of the International Boundary. With this exception, practically nothing was known geologically concerning the area in which the writer was engaged during the summers of 1911 and 1912, previous to the commencement of this work.

TOPOGRAPHY

Topographically, the area or belt along the 141st meridian between Yukon and Porcupine rivers lies for the greater part at least within the

² R. G. McConnell: Report on an exploration in the Yukon and Mackenzie basins, Northwest Territory. Geol. and Nat. Hist. Surv. of Canada., Ann. Rept., vol. iv, 1888-1889, part D, pp. 129-134.

³ E. M. Kindle: Geologic reconnaissance of the Porcupine Valley, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 310-338.

⁴ Op. cit., pp. 134D-143D.

⁵ J. E. Spurr: Geology of the Yukon Gold district, Alaska. U. S. Geological Survey, 18th Ann. Rept., part iii, 1896-1897, pp. 89-382.

⁶ L. M. Prindle: The gold placers of the Forty-mile, Birch Creek, and Fairbanks regions, Alaska. U. S. Geological Survey, Bull. No. 251, 1905.

⁷ Alfred H. Brooks and E. M. Kindle: Paleozoic and associated rocks of the Upper Yukon, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 255-314.

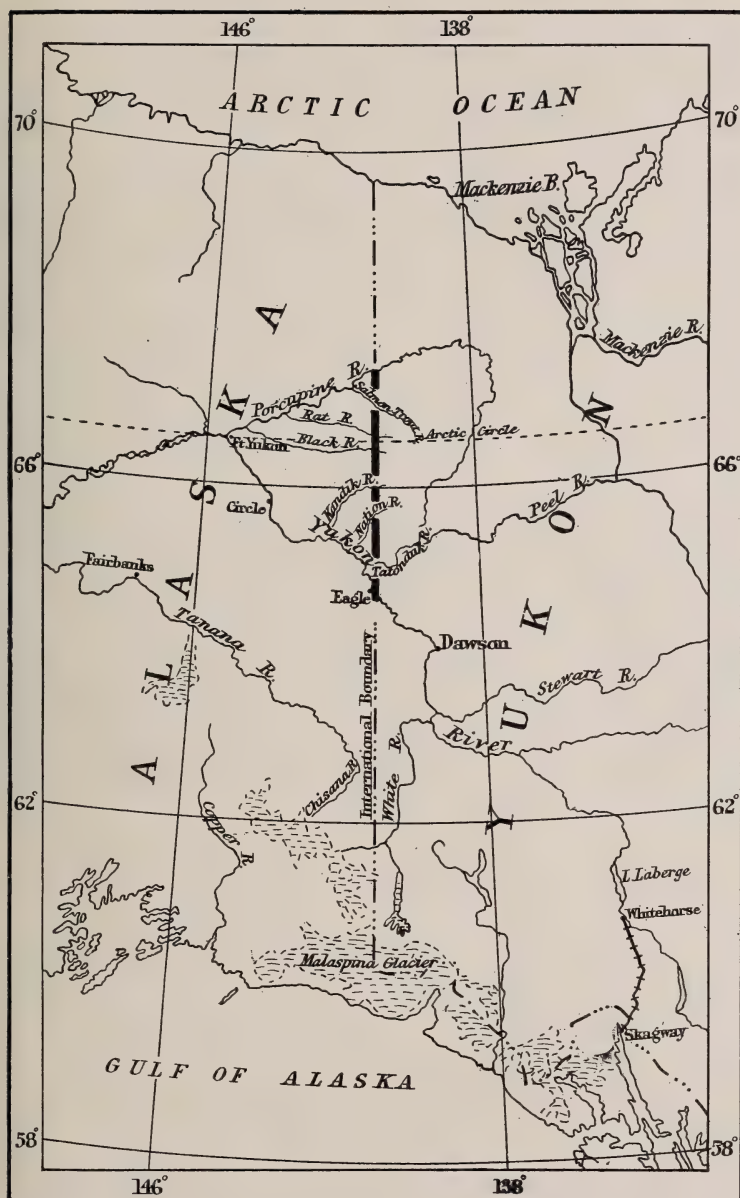


FIGURE 1.—Sketch Map showing Yukon-Alaska International Boundary Line

The portion of the Boundary indicated by heavy line was mapped and studied geologically during 1911 and 1912 by D. D. Cairnes for the Canadian Geological Survey

Yukon Plateau province; and since this physiographic terrane in the vicinity of the 141st meridian has a general westerly trend, it is cross-cut by the meridian practically at right angles. Thus, in going from New Rampart on the Porcupine, south to Yukon River, the line of travel is transverse to the trend of the main topographic features of the district, and consequently a considerable diversity of topography is encountered.

In certain localities where the prevailing bedrock is limestone or dolomite, the plateau characteristics are still well preserved, and extensive tracts of upland occur having elevations of 3,000 feet or more above sea-level. With the exception of these areas, the original plateau surface has been almost or entirely destroyed, and throughout the greater part of the district the land surface has become thoroughly dissected.

Two ranges or mountain groups are crossed by the boundary line, which have summits rising to elevations exceeding 5,000 feet above sealevel, and it is possible that one or both of these may be connected with the Rocky Mountain system to the west, and thus constitute outlying lobes of that physiographic terrane. It is more probable, however, that these are but isolated mountainous areas included within the Yukon plateau. To the north and south of these more rugged and mountainous areas, as well as between them, the topography consists dominantly of well rounded, irregularly distributed hills, and at frequent intervals throughout the district westerly flowing streams are encountered which have in most places deep, steep-walled valleys, the floors of which are as much as 5 miles in width and from 900 to 1,200 feet in elevation above the sea. Nowhere was any evidence of glaciation noted.

GENERAL GEOLOGY

GENERAL STATEMENT

The geological formations along the 141st meridian between Yukon and Porcupine rivers are dominantly of sedimentary origin, but include some intrusives and also a group of metamorphic rocks, the origin of some of the members of which is uncertain. The sedimentary members range in age from Recent to Middle Cambrian, and include as well a group of rocks—the Tindir group—the members of which are either Lower Cambrian or possibly pre-Cambrian in age; and not only are Mesozoic and these possibly pre-Cambrian beds somewhat extensively developed, but in addition each of the five systems of the Paleozoic from the Cambrian to the Carboniferous is represented. Occasional dykes and small intrusive bodies pierce the Mesozoic and Paleozoic beds in places, and greenstones of various types have a considerable development in association with cer-

tain of the Lower Cambrian or pre-Cambrian members, and occur as sills, dikes, or larger irregular intrusive masses. The metamorphic rocks are dominantly schistose in character, and within the area here being considered are mainly at least of sedimentary origin. These are developed only along Yukon River and are thought to be the oldest rocks in the district.

The metamorphic schistose rocks are all included under the term Yukon group, the members of which within the belt here particularly under consideration consist dominantly of schistose amphibolites, quartzite schists, mica schists, and occasional beds of limestone. The evidence obtainable concerning these rocks indicates rather conclusively that they are all of pre-Cambrian age. The members of the Tindir group may also prove to be of pre-Cambrian age, and are at least older than Middle Cambrian. This group of rocks is composed mainly of dolomites, quartzites, shales, sandstones, and associated greenstones, which are considered to be almost undoubtedly younger than the members of the Yukon group. The Tindir group is overlain unconformably by a thick series of limestone and dolomite beds which range in age from Cambrian to Carboniferous. In the northern portion of the belt, beds of this character, all lithologically very similar, overlie the Tindir members, and include beds ranging from Middle and possibly also Lower Cambrian age to Pennsylvanian, all the Paleozoic systems being represented. Toward the south the upper members are gradually eliminated, and the time interval becomes represented by more arenaceous, argillaceous, and siliceous beds, including mainly sandstones, conglomerates, shales, slates, and cherts, with some intercalated thin beds of limestone. Thus by the time Harrington Creek is reached, at latitude $65^{\circ} 05'$, the limestone-dolomite beds range upward from Cambrian to and include Devonian members, which are overlain by Devonian and Carboniferous shales, slates, cherts, and thinly bedded limestones. About 10 miles farther south the shales, slates, cherts, and thinly bedded limestones range in age from Carboniferous down to and include Ordovician members which there overlie Ordovician and Cambrian limestones and dolomites. Thus toward the south the argillaceous and arenaceous members are more persistent, and the limestone-dolomite members represent a much shorter time interval than farther north. In the northern part of the belt Mesozoic-Pennsylvanian sediments comprising the Orange group, and consisting dominantly of shales, sandstones, conglomerates, slates, and quartzites, as well as occasional limestone beds containing Pennsylvanian fossils, overlie the older terranes. This is the most extensively developed formation along the 141st meridian between Yukon and Porcupine rivers. Farther south the Mesozoic beds were not recognized, but lithologically somewhat similar conglomerates, sandstones,

and shales of the Nation River formation, generally considered to be of Pennsylvanian age, succeed the Carboniferous shale series. More recent than all these consolidated rock formations are the superficial deposits of Recent and Pleistocene times, which constitute a mantle obscuring the older geological terranes, more or less, throughout the entire district.

On the accompanying table of formations three typical sections are shown, which are characteristic of the geological succession, so far as this is known, in the northern, intermediate, and southern portions of this belt along the 141st meridian. Since, however, the stratigraphy changes much more rapidly toward the south than farther north, the northern section applies to considerably the greater part of the belt, the intermediate and southern sections referring only to the southern portion of the area. Also, although the stratigraphy of the Paleozoic era varies so greatly in that district, there are all gradations between the sections, as illustrated in the table, these having been selected as being typical of extreme phases. The rapid changes in stratigraphy, particularly to the south of Harrington Creek, are thought to be largely accounted for by the fact that the 141st meridian, along which the sections were measured, lies practically at right angles to the general trend of the geological structures and developments of the region.

METAMORPHIC ROCKS

Pre-Cambrian (?)—Yukon group.—The members of the Yukon group are exposed along the northern side of Yukon River, throughout an area which within the belt mapped along the 141st meridian has an extent of from 3 to 5 square miles. This constitutes the only known occurrence of these rocks exposed along the Yukon-Alaska boundary line between Porcupine and Yukon rivers, but this exposure constitutes a peripheral portion of an extensive development of these rocks to the south of the river.

The members of this group are dominantly schistose in structure, and within this particular area consist mainly of quartzite schists, schistose amphibolites, and mica schists. All these rocks are much folded, faulted, and distorted, and are so metamorphosed that in places it is difficult or impossible to determine their origin or original characters.

Included in these schistose rocks there occur occasional beds or small, irregular masses of limestone, which in places appear to represent infolded portions of more recent beds which formerly overlay the older rocks. At one point at least on the south side of Yukon River such proved to be the case, as there the limestone was found to contain an abundance of Paleozoic crinoid stems. In other places, however, the limestone is inter-

Southern section		Remarks
Thickness in feet	Lithological characters	
	Gravels, sands, clays, peat, soil and ground-ice	
		Probably corresponds to the Laberge series of Yukon. Contains invertebrate remains
4,000 +	Conglomerates, sandstones, and shales	Reddish conglomerate may represent former Permo-Carboniferous glacial period
		Nation River formation contains abundance of plant remains
600 +	Interbedded black, gray, and red shales and cherts, including some calcareous shales	All Carboniferous limestones contain abundance of invertebrate remains
3,000 +	Limestones and dolomites, dominantly very siliceous	Unmetamorphosed Devonian, Silurian, Ordovician, and Upper and Middle Cambrian beds are fossiliferous. Several hundred feet of unfossiliferous limestones and dolomites, considered to be probably Lower Cambrian, underlie the beds which contain Middle Cambrian fossils
		Unfossiliferous Indurated, but only slightly metamorphosed
(?)	Schistose amphibolites, quartzite schists, and mica schists; also includes occasional limestone beds	Highly metamorphosed It is from the members of this group that the placer gold in the Klondike and other important mining districts in Yukon and Alaska has been derived
		Occur only as occasional dikes and small intrusive masses
(?)	Diabases, diorites, andesites and other basic intrusives	Occur dominantly associated with pre-Cambrian (?) formations. Similar appearing rocks also occur as occasional dikes and small intrusive masses cutting Mesozoic sediments

TABLE OF FORMATIONS
Dominantly Sedimentary Rocks

Era	Period		Northern section			Intermediate section			Southern section			Remarks
			Formation	Thickness in feet	Lithological characters	Formation	Thickness in feet	Lithological characters	Formation	Thickness in feet	Lithological characters	
Quaternary	Recent and Pleistocene		Superficial deposits		Gravels, sands, clays, peat, soil and ground-ice	Superficial deposits		Gravels, sands, clays, peat, soil and ground-ice	Superficial deposits		Gravels, sands, clays, peat, soil and ground-ice	
Mesozoic	Probably mainly Lower Cretaceous		Orange group	4,000	Conglomerates, sandstones, shales, slates, phyllites, and quartzites, as well as occasional limestone beds in lower portion of group							Probably corresponds to the Laberge series of Yukon. Contains invertebrate remains
Paleozoic	Carboniferous	Permian		2,000			800 +	Reddish conglomerate containing considerable iron in places, possibly consolidated boulder clay	Nation River formation	4,000 +	Conglomerates, sandstones, and shales		Reddish conglomerate may represent former Permo-Carboniferous glacial period
		Pennsylvanian	Racquet group	1,500 +	Dominantly white to grayish limestones, containing considerable chert in places, and also some shales and occasional cherty conglomerate beds	Apparently includes Calico Bluff formation	800 +	Interbedded limestones and shales, dominantly calcareous				Nation River formation contains abundance of plant remains
		Mississippian										
	Devonian		Includes Salmontrout limestone	300 +	Light to dark gray crystalline limestone		300 +	Interbedded black, gray, and red shales and cherts	600 +	Interbedded black, gray, and red shales and cherts, including some calcareous shales	Unmetamorphosed Devonian, Silurian, Ordovician, and Upper and Middle Cambrian beds are fossiliferous. Several hundred feet of unfossiliferous limestones and dolomites, considered to be probably Lower Cambrian, underlie the beds which contain Middle Cambrian fossils	
	Silurian											
	Ordovician			4,000 +	Limestones and dolomites, dominantly very siliceous		4,000 +	Limestones and dolomites, dominantly very siliceous				
	Cambrian									3,000 +	Limestones and dolomites, dominantly very siliceous	
Unconformity												
Lower Cambrian or pre-Cambrian			Tindir group	5,000 +	Dolomites, quartzites, and shales, with some included greenstones	Tindir group	5,000 +	Dolomites, quartzites, and shales, with some included greenstones				Unfossiliferous Indurated, but only slightly metamorphosed
Unconformity (?)												
Metamorphic rocks												
Pre-Cambrian (?)									Yukon group	(?)	Schistose amphibolites, quartzite schists, and mica schists; also includes occasional limestone beds	Highly metamorphosed It is from the members of this group that the placer gold in the Klondike and other important mining districts in Yukon and Alaska has been derived
Igneous rocks												
Mesozoic				(?)	Granites, granodiorites, and syenites							Occur only as occasional dikes and small intrusive masses
Range from Mesozoic to pre-Cambrian				(?)	Diabases, diorites, andesites, and other basic intrusives		(?)	Diabases, diorites, andesites, and other basic intrusives		(?)	Diabases, diorites, andesites and other basic intrusives	Occur dominantly associated with pre-Cambrian (?) formations. Similar appearing rocks also occur as occasional dikes and small intrusive masses cutting Mesozoic sediment

calated somewhat regularly, and has every appearance of being and probably is contemporaneous with the schistose members. This limestone has become completely altered into marble and is in most places much sheared and brecciated.

The name Yukon group⁸ was first employed by the writer to designate these rocks along the 141st meridian,⁹ and is intended to include all these older metamorphosed, schistose, and gneissoid rocks both of sedimentary and igneous origin. Similar schistose and gneissoid rocks are extensively developed in portions of Yukon and Alaska, and practically all geological workers who have recently studied them have considered these rocks to constitute the oldest geological terrane in the particular district investigated. These rocks have thus been variously classed as pre-Devonian, pre-Silurian, and pre-Ordovician, according to the age or supposed age of the oldest overlying beds. In summing up the information concerning these rocks in the Upper Yukon basin, Brooks and Kindle state:¹⁰ "The data at hand justify the statement that below the rocks of known age (certainly older than Devonian and probably than the Ordovician) there is a complex of metamorphic sediments and igneous rocks which is widely distributed in the Upper Yukon basin." These writers class these rocks as pre-Ordovician.¹¹

The small development of schistose rocks included in the belt along the 141st meridian, here being considered, constitutes a peripheral portion of an extensive development of these older metamorphic rocks described by the above mentioned authors, the extent of these rocks along the Upper Yukon, Alaska, being indicated approximately on figures 1 and 2 in the paper to which reference has just been made. These rocks are considered by these writers to be pre-Ordovician, as the oldest fossil remains found in the overlying limestones are of Ordovician age. The finding by the writer of Middle Cambrian fossils in the corresponding limestones along the 141st meridian thus throws additional light on the age of these metamorphic rocks. As is mentioned in describing the Tindir group, these rocks underlie a thick series of limestone-dolomite beds, and Middle Cambrian fossils occur in the limestones some distance from the bottom of the series. It would thus appear as possible that the Lower Cambrian is represented by the lowest beds of the limestone-dolomite series. In any case the Tindir group is either Lower Cambrian or pre-Cambrian. There is

⁸ It is realized that the term "Yukon silts" has been previously applied to the silts of the Yukon basin, still it is not considered that this will conflict with the use of the term "Yukon group" for the pre-Cambrian (?) metamorphic rocks of the North.

⁹ D. D. Cairnes: Along portions of the Yukon-Alaska International Boundary line between Yukon and Porcupine rivers. Geol. Surv. of Canada, Sum. Rept. for 1912.

¹⁰ A. H. Brooks and E. M. Kindle: Paleozoic and associated rocks of the Upper Yukon, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, p. 270.

¹¹ Ibid., pp. 264-271.

no place also in the complete Paleozoic section found to occur in the district for the extensive, thick, Yukon group, and it is difficult to conceive how the Yukon group could be a metamorphosed phase of the Tindir group, considering the compositions of the component members of the two groups, and considering further that the two groups are extensively developed and both preserve wherever found their peculiar, distinctive, and very different lithological characteristics. Further, just north of Yukon River along the 141st meridian some phyllites occur overlying the members of the Yukon group, and as these phyllites closely resemble certain members of the Tindir group, and are unlike any of the other rocks seen along the boundary, it seems probable that these are Tindir beds, and, if so, the members of the Yukon group are decidedly the older.

Therefore, although the typical and definitely identifiable members of the Tindir group were not found by the writer in actual contact with the rocks of the Yukon group, unless the phyllites previously referred to belong to the Tindir, still for the reasons above mentioned it seems as if there could remain but little doubt that the members of the Yukon group are the oldest rocks in the Yukon Valley and that they are of pre-Cambrian age.

The schistose rocks of the Yukon Valley have been subdivided by various writers and have been given a number of formational names, and it seems probable that the greater number of these divisions are included by the term Yukon group. This group thus probably includes the Nasina series, as described by Brooks¹² and McConnell,¹³ and also McConnell's Klondike series¹⁴ and Pelly gneisses,¹⁵ as well, possibly, as his Moosehide diabase.¹⁶ McConnell has also correlated the Birch Creek¹⁷ series and Forty-mile series,¹⁸ as described by Spurr, with the Nasina series, so these rocks are also probably included.

The Tanana schists as described by Brooks¹⁹ and Mendenhall²⁰ may

¹² A. H. Brooks: A reconnaissance in the White and Tanana River basins, Alaska, in 1898. U. S. Geological Survey, 20th Ann. Rept., part vii, pp. 465-467.

¹³ R. G. McConnell: Report on the Klondike gold fields. Geol. Surv. of Canada, Ann. Rept., vol. xiv, part B, 1901, pp. 12B-15B.

¹⁴ *Ibid.*, 15B-22B.

¹⁵ A. H. Brooks: *Op. cit.*, pp. 460-463.

R. G. McConnell: Note on the so-called basal granite of Yukon Valley. *The American Geologist*, vol. xxx, July, 1902, pp. 55-62.

¹⁶ R. G. McConnell: Report on the Klondike gold fields. Geol. Surv. of Canada, Ann. Rept., vol. xiv, part B, 1901, pp. 22B-23B.

¹⁷ J. E. Spurr: Geology of the Yukon Gold district, Alaska. U. S. Geological Survey, 18th Ann. Rept., part iii, 1896-1897, pp. 140-145.

¹⁸ *Ibid.*, pp. 145-155.

¹⁹ A. H. Brooks: A reconnaissance in the White and Tanana River basins, Alaska, in 1898. U. S. Geological Survey, 20th Ann. Rept., part vii, 1898-1899, pp. 468-470.

²⁰ W. C. Mendenhall: A reconnaissance from Resurrection Bay to the Tanana River, Alaska, in 1898. U. S. Geological Survey, 20th Ann. Rept., 1898-1899, pp. 313-315.

also be included in the Yukon group, as well probably as the Greenstone schists²¹ described by these writers and others. Brooks has also used the name Kotlo series²² in a general way to include all the older sedimentary rocks which he regards as of Lower Paleozoic or pre-Cambrian age, but also adds that "this series is of especial interest, because it probably embraces all the gold-bearing rocks of the Upper Yukon."²³ McConnell has shown, however, that the Klondike series are the principal gold-bearing rocks of the Klondike district, and these rocks are dominantly of igneous origin. From the descriptions of the Kotlo series, therefore, it seems somewhat doubtful whether or not only rocks of sedimentary origin are intended to be included. Thus the name Kotlo series may be synonymous with the term Yukon group, but it would appear as more probable that the later name is the more comprehensive and includes the former.

The members of the Yukon group occurring within the particular belt along the 141st meridian, described in this paper, are, dominantly at least, of sedimentary origin, and thus belong to the Nasina series. The name Yukon group is used, however, to avoid chance of error in correlation, as it is necessary to know the origin of the schistose member to be able to apply the other formational names that have been employed. It is also thought that the term Yukon group should be a useful field name, as under this group may be included all older metamorphic, probably pre-Cambrian, schistose and gneissoid rocks that are encountered, regardless of their origin, which is often difficult or impossible to determine.

The writer recognizes the difficulty that exists in dealing with these older rocks, and also realizes that in many places there exists a great amount of uncertainty concerning their age and origin. Still it seems fairly certain that there does exist a pre-Cambrian metamorphic complex underlying all the sedimentary rocks of known age in the Upper Yukon Valley and other portions of Yukon and Alaska; also these rocks, which have previously been considered to be pre-Ordovician or younger, would now appear to be all or at least dominantly of pre-Cambrian age.

DOMINANTLY SEDIMENTARY ROCKS

Lower Cambrian or pre-Cambrian—Tindir group.—The members of the Tindir group within the particular area under consideration in this paper are exposed mainly in two localities, namely, along Porcupine River, in the northern end of the district, and between Ettrain and Harrington creeks, nearly 150 miles farther south. These rocks extend along

²¹ A. H. Brooks: Op. cit., p. 470.

²² A. H. Brooks: A reconnaissance from Pyramid Harbor to Eagle City, Alaska. U. S. Geological Survey, 21st Ann. Rept., part ii, 1899-1900, pp. 357-358.

²³ Ibid., p. 358.

both sides of the Porcupine for a number of miles both above and below the mapped five-mile strip, and continue to the south of the river along the boundary line for about 4 miles, to where they are overlain by Paleozoic limestones and dolomites. To the south, these rocks again come within the boundaries of the mapped area at a point about 5 miles south of Ettrain Creek, and continue southward along the eastern edge of this belt to within half a mile of Cathedral Creek, a distance of about 10 miles. From Cathedral Creek southward for 4 to 7 miles these rocks extend over the entire width of the mapped belt, and to the east of this belt they were seen to be extensively developed.

The Tindir rocks on Porcupine River were noted by McConnell²⁴ in 1888, and have since been described somewhat in detail by Kindle²⁵ and Maddren,²⁶ who class them as "pre-Ordovician," but have not given them any formation name. To these particular rocks exposed along the Porcupine, therefore, the writer has applied the name Tindir group.

The members of the Tindir group in this original locality consist dominantly of quartzites, dolomites, shales, and sandstones, with which are associated some intrusive greenstones. Wherever any considerable section of these rocks are exposed, as along Darcy Creek, a tributary of the Porcupine, the different members present a bright vari-colored appearance—yellow, red, gray, and black beds being most prominent. Also along Porcupine River the sharp contrast between the exposures of the intensely black shales and the white to grayish quartzites and dolomites, which weather to a creamy or yellowish color in places, constitutes one of the most striking scenic features of the Upper Rampart gorge in the vicinity of the boundary line.

This entire group of rocks has been considerably folded, faulted, and distorted, so that it is difficult to estimate the aggregate thickness of the beds in sight, and the bottom of the group was not observed. It would appear, therefore, that this group of rocks on the Porcupine has a thickness of at least 5,000 feet and may be much thicker in places.

The shales, being softer and less competent to resist the various stresses and strains to which they have been subjected, have become much more crumpled, mashed, broken, and distorted than the dolomites and quartzites, and within a few feet in places folds may be observed in all attitudes, ranging from upright to completely reversed, with numerous faults of

²⁴ R. G. McConnell: Report on an exploration in the Yukon and Mackenzie basins, Northwest Territory. Geol. and Nat. Hist. Surv. of Canada, Ann. Rept., vol. iv, 1888-1889, part D, pp. 129-134.

²⁵ E. M. Kindle: Geologic reconnaissance of the Porcupine Valley, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 320-322.

²⁶ A. G. Maddren: Geologic investigations along the Canada-Alaska boundary. U. S. Geological Survey, Bull. 520-K, 1912, pp. 6-11.



FIGURE 1.—LOOKING DOWN PORCUPINE RIVER FROM INTERNATIONAL BOUNDARY LINE
All the rock exposures in the ramparts here belong to the Tindir group



FIGURE 2.—LOOKING DOWN DARCY CREEK TOWARD PORCUPINE RIVER
All rock outcrops in this view belong to Tindir group
TINDIR SECTIONS IN VICINITY OF PORCUPINE RIVER

varying displacement intersecting the beds in different directions. Although these beds are so greatly disturbed, metamorphism is not pronounced in the different members of the group, and the rocks themselves, although considerably indurated, have nowhere, for instance, a schistose or gneissoid structure, and seldom, if anywhere, possess a slaty cleavage. They are thus very different in this respect from the members of the Yukon group.

Occasional dikes and small intrusive masses of diabase pierce these rocks in places, and since the dikes rarely extend up into the overlying Paleozoic rocks, the diabase is probably older than the latter.

These rocks, where exposed to the south along Tindir Creek and between Ettrain and Harrington Creek, resemble very closely those on the Porcupine; to the south, however, greenstones are developed to a much greater extent, and the quartzites instead of being dominantly white to grayish include more greenish, reddish, and dark colored members. As to the north, the Tindir rocks here are characteristically brightly and varicolored, and the hills on which they outcrop can generally be distinguished for several miles, these bright colored rocks constituting one of the most striking features of the landscape.

To the north of Harrington Creek the members of the Tindir group distinctly underlie unconformably the Cambrian limestone-dolomite beds of Jones ridge; and along Porcupine River, also, the Tindir rocks are evidently overlain by the limestone-dolomite beds, in which Middle Cambrian fossils were found. Below the horizon from which these Middle Cambrian remains were obtained, there occur in places several hundred feet of lithologically similar, but unfossiliferous, limestones and dolomites, which in all probability represent the Lower Cambrian, and underlying these beds unconformably occur the Tindir rocks. The members of the Tindir group are thus either of Lower Cambrian or pre-Cambrian age. Considering, however, the great thickness of these rocks, the fact that they differ so greatly lithologically from the overlying beds of Middle and Upper Cambrian age, and that the Lower Cambrian is probably represented by the lowest beds of the overlying limestone-dolomite formation, from which lowest beds no fossils have as yet been obtained, it would seem to the writer very probable either that the Tindir rocks are entirely of pre-Cambrian age or that this group includes both Lower Cambrian and pre-Cambrian members.

The Tindir group appears to correspond to the Belt Terrane²⁷ of Brit-

²⁷ R. A. Daly: *Geol. Surv., Canada, Memoir No. 38, 1912, pp. 179-191.*

S. J. Schofield: *Geological reconnaissance in East Kootenay, British Columbia. Sum. Rept. 1912, Geol. Surv., Canada. See section on correlation.*

C. R. Van Hise and C. K. Leith: *Pre-Cambrian geology of North America. U. S. Geological Survey, Bull. 360, 1909, pp. 98, 852, 856-857, 858, 860-864, 881.*

ish Columbia and the Western States, which is officially considered by the United States Geological Survey to represent the latest Algonkian. As the age of these Beltian rocks is still disputed, and as correlation between formations so widely separated geographically is always open to criticism, the writer has adopted the new term Tindir group for these rocks along the Alaska-Yukon boundary, although lithologically they appear to be strikingly similar to the Beltian rocks, and these latter are also thought by most writers to occupy a position stratigraphically corresponding to that assigned here to the Tindir group.

Further, as the members of the Tindir group are but slightly metamorphosed, and as the rocks of the Yukon group are so highly metamorphosed, and since, also, as previously explained, the Yukon group is thought to be almost undoubtedly older than the Tindir group, an unconformity is supposed to exist between these formational groups. As before mentioned, however, the writer did not observe the members of the Yukon group in direct contact with rocks that could be positively identified as belonging to the Tindir group. If the phyllites along Yukon River prove to belong to the Tindir group, as the writer is inclined to think they do, the supposed unconformity is established, as these phyllites rest unconformably on the members of the Yukon group.

It would thus now appear as very probable that the pre-Cambrian is extensively developed in portions of Yukon Valley and elsewhere in Yukon and Alaska, and that these rocks are divisible into an upper but slightly metamorphosed division, the Tindir group, and a lower highly metamorphosed division, the Yukon group. The writer is quite well aware, however, of the difficulties that may possibly arise in attempting to use a classification of this kind with the information at hand, and also realizes the uncertainty attending any attempt to measure the ages of rock groups by the mystic scale of metamorphism; still it is thought that this classification, owing to its simplicity, may prove useful in case the pre-Cambrian age of the Tindir and Yukon groups becomes established. It is realized, however, that the problem concerning these older rocks is yet far from being solved, and that a great amount of work still remains to be performed before the intricacies of this extremely interesting problem will be understood.

Devono-Cambrian limestones and dolomites.—A series of limestone-dolomite beds, including members of Cambrian, Ordovician, Silurian, and Devonian age, are extensively developed along the 141st meridian between Porcupine and Yukon rivers, and throughout the belt these rocks have everywhere the same lithological characteristics, so much so that it is impossible in most places to determine, even approximately, the age of the

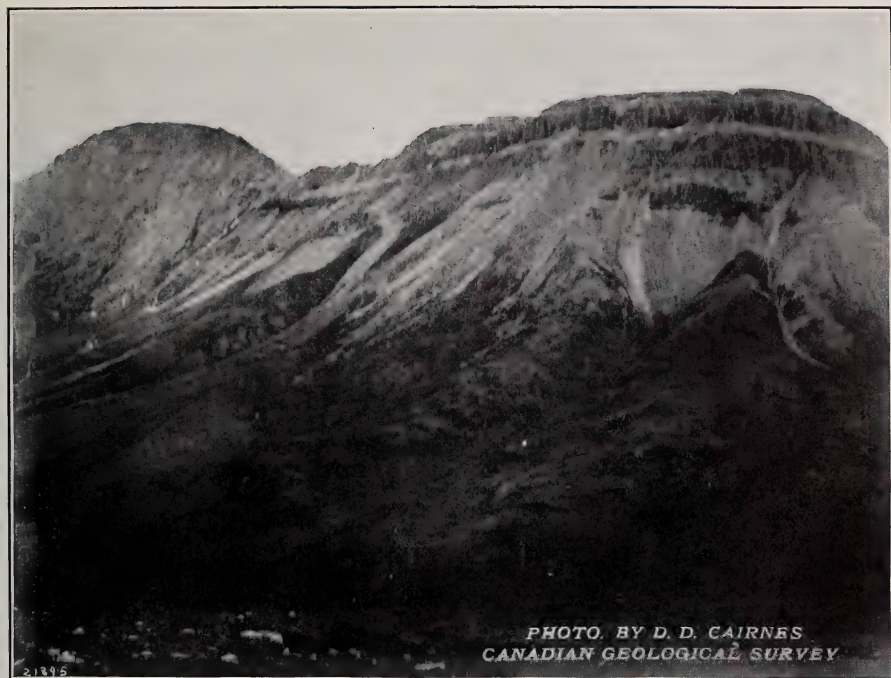


FIGURE 1.—LOWER PALEOZOIC LIMESTONES AND DOLOMITES FORMING THE SUMMIT OF MOUNT SLIPPER, OVERLYING TINDIR SHALES



FIGURE 2.—TYPICAL DEVELOPMENT OF LOWER ORDOVICIAN AND CAMBRIAN LIMESTONES AND DOLOMITES

The locality is just north of MaCann Hill. The limestones and dolomites on the mountain top in the foreground are overlain, apparently conformably, by Ordovician shales

CAMBRIAN AND PRE-CAMBRIAN (?) BEDS, YUKON-ALASKA BOUNDARY LINE

beds on lithological evidence alone. As shown on the table of formations, these limestones and dolomites persist in the northern portion of the belt, from the Devonian down to and including portions at least of the Cambrian. Going southward, however, these beds give place gradually to the shale series, so that to the south of Tatonduk River only Cambrian and the lower portion of the Ordovician are represented by these beds. To the north on Harrington Creek the limestone-dolomite series extends upward to and including portions of the Devonian and is overlain by Devonian shales.

These beds in the northern portion of the belt have an aggregate thickness of at least 4,000 feet, and possibly much more than this amount, but no section of them was at all closely measured at any one point, it having been found very difficult to do so on account of folding and faulting, and owing also to the fact that the beds are lithologically very similar throughout, and thus include practically no stratigraphical horizon markers. To the south, these beds do not appear to be so thick, but even there they have an aggregate thickness of at least 3,000 feet.

These rocks are prevailingly white to light gray in color, but occasional beds occur having a dark gray to nearly black or even a pink or reddish appearance. Nearly everywhere, however, on weathered surfaces the different members have the peculiar grayish to bluish gray, rough appearance characteristic of limestones. The rocks are dominantly crystalline, and in places beds of particularly beautiful marble occur, ranging from pure white through various shades of gray, and even occasional reddish beds were noted. In texture these limestones and dolomites vary from firm, dense dolomites to coarsely crystalline almost pure limestones. They are also characteristically somewhat massive in appearance, due largely to the degree of metamorphism which they have suffered; but where the bedding planes are discernible the strata are dominantly from 1 to 6 feet in thickness, although much thinner beds, from 1 to 6 inches thick, are locally characteristic of the series. Beds of limestone having an oolitic structure also occur to the south of Tatonduk River and elsewhere, the oolitic grains being generally about one-tenth of an inch or less in diameter. In a few places grayish, yellowish to nearly black shales are intercalated with these limestone-dolomite beds, and at one point on the western side of Mount Slipper over 200 feet of thinly bedded shales occur, with dolomites above and below them. Shales, however, are of very minor importance quantitatively in this terrane. The entire series is very siliceous, and toward the south the beds contain a great amount of translucent to semi-translucent chalcedonic quartz or chert, which in places considerably exceeds the limestone and dolomites in amount. This chert has in places

been deposited largely along the bedding planes of the containing rocks in seams ranging from microscopic up to 8 or 10 inches in thickness, and thus gives the rocks in general a decidedly banded appearance. When somewhat regularly deposited along the bedding planes in this way, the chert has in places the appearance of being contemporaneous with the containing beds, but when more closely examined it may be seen to intersect the strata; in fact, seams or masses of chert occur cutting the limestone and dolomite beds at all angles, and the smaller seams are frequently distinctly traceable back to larger seams or irregular bodies.

The entire series of rocks ranging through the Silurian, Ordovician, and Cambrian appears to be conformable throughout, and it was found to be impracticable, if not impossible, to differentiate and map separately the beds of the different ages. The rocks are all so much folded and faulted that only in a few places could the positions of the different beds within the series be even approximately determined stratigraphically; and unless fossils could be found it was impossible, even in these places, to draw the geological age-boundaries, as no distinctive persistent lithological horizon markers could be distinguished, such as occur in less uniform formations in many districts and serve to indicate the position of geological boundaries in the absence of fossil remains. Fossils, moreover, are of somewhat rare occurrence in these beds, particularly in the lower members, so that a great amount of detailed paleontological and stratigraphical work would be required to subdivide these rocks and map them according to their respective ages.

The Devonian beds, however, are dominantly or entirely limestones, which have an aggregate thickness of from 300 to 500 feet. In places it is difficult or impossible, except paleontologically, to distinguish these rocks from the underlying limestone beds, but as a rule they are somewhat more homogeneous and darker in appearance, being typically dark bluish gray in color. They are also in most places more coarsely crystalline, and when broken they characteristically emit a strong oily odor, which was not noted to the same extent in connection with the underlying formations. In places a heavy bed or series of beds of white to light gray, sugar-grained quartzite occurs at the base of this series, but this appears to be only locally developed. These beds, wherever a contact was observed, overlie the Silurian beds unconformably.

The Devonian limestone corresponds somewhat closely to the Salmon-trout limestone on Porcupine River, as described by Kindle,²⁸ and the two formations may be the same. It would seem probable, however, that the

²⁸ E. M. Kindle: *Bull. Geol. Soc. Am.*, vol. 19, Oct., 1908, pp. 327-329.



FIGURE 1.—TYPICAL VIEW OF THE ELEVATED PLAIN-LIKE SURFACE OF KEELE MOUNTAINS

These mountains are situated near the northern end of the belt. Here the plateau surface is well preserved, due to the resistance of the composing limestones and dolomites to subaerial destructive agencies.



FIGURE 2.—CLOSE VIEW OF ONE OF THE RUGGED VALLEY WALLS IN THE OGILVIE MOUNTAINS

These mountains are situated near the southern end of the belt. They do not appear to have been planated, but probably originally constituted a residual mountainous area, at the close of the last period of baseleveling.

**MOUNTAIN GROUPS COMPOSED ALMOST ENTIRELY OF PALEOZOIC LIMESTONES
AND DOLOMITES**

Salmontrout limestone as originally defined does not include all the Devonian limestones along the boundary line, and thus the name is not sufficiently comprehensive to apply to the beds here described.

This entire Devono-Cambrian limestone-dolomite group corresponds lithologically very closely with the Paleozoic limestone section described by Prindle²⁹ as occurring in the Fairbanks Quadrangle, Alaska; in fact, the entire geologic section described in this bulletin resembles in many ways the section along the 141st meridian. The faunas from this Devono-Cambrian group along the 141st meridian appear to correspond somewhat closely to those of the Port Clarence limestone,³⁰ according to Dr. E. M. Kindle, who has examined the fossils from both of these regions. The Port Clarence limestones are typically developed in the western part of Seward Peninsula, Alaska, and the faunas of this formation represent the nearest geographic approach of American fossil faunas to those of Asia.

The fossils obtained from this limestone-dolomite series along the boundary are of particular interest on account of the Cambrian remains as well as the graptolites which they include. Cambrian fossils were found in several localities along the boundary, but had not previously been reported from Yukon Territory, and have been found in only one locality in Alaska, which is situated in Seward Peninsula, over 700 miles to the west.³¹ The nearest Canadian locality in which Cambrian fossils are known to have been discovered is on Gravel River, in the Northwest territories, over 400 miles to the southeast.³² Graptolites are believed to have been previously found in only two localities in Alaska, namely, in the Mount McKinley region³³ and on Porcupine River,³⁴ and had been discovered in places in Yukon in only one locality.³⁵

The Cambrian fossils collected by the writer along the Yukon-Alaska boundary have all been examined by Mr. L. D. Burling, of the Canadian

²⁹ E. M. Prindle: A geologic reconnaissance of the Fairbanks Quadrangle, Alaska. U. S. Geological Survey, Bull. 525, 1913, pp. 39-47.

³⁰ A. J. Collier: A reconnaissance of the northwestern portion of Seward Peninsula, Alaska. U. S. Geological Survey, Prof. Paper No. 2, 1902, pp. 18-21.

E. M. Kindle: The faunal succession in the Port Clarence limestone, Alaska. Amer. Jour. Sci., vol. xxxii, Nov., 1911, pp. 335-349.

³¹ E. M. Kindle: *Ibid.*, pp. 340-343.

³² Joseph Keele: A reconnaissance across the Mackenzie Mountains on the Pelly, Ross, and Gravel rivers, Yukon and Northwest territories. Geol. Surv., Canada, No. 1097, 1910, pp. 36, 37.

³³ Alfred H. Brooks: The Mount McKinley region, Alaska, with descriptions of the igneous rocks and of the Bonfield and Kautishna districts, by L. M. Prindle. U. S. Geological Survey, Prof. Paper No. 70, 1911, pp. 72-73.

³⁴ E. M. Kindle: Geologic reconnaissance of the Porcupine Valley, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 325-326.

³⁵ Joseph Keele: *Op. cit.*, p. 35.

Geological Survey, who has identified several horizons within the Upper and Middle Cambrian.³⁶

Of the Ordovician remains the graptolites were sent to Doctor Ruedemann, and the other specimens were examined by Dr. E. M. Kindle and Mr. Burling, both of the Canadian Geological Survey. Doctor Ruedemann reports as follows:

"While the specimens were not so excellently preserved that one would be very positive in their determination, I am fairly sure that the three following forms are present:

Dicranogr. cf. ramosus (Hall).

Retiograptus geinitizianus Hall.

Diplogr. (foliaceus var.) *incisus* Lapworth.

"The *Dicranogr.* is only represented by broken fragments of branches. These show, however, in one or two places, the strongly introverted thecae of the later *Decranograpti*. The *Retiograptus* shows a number of interesting structural features as the straight and zigzag axes, and it would be hardly more than varieties different from Hall's species.

"The *Diplograptus* is rather poorly preserved. It resembles, in my opinion, most the form formerly referred to as a var. of *foliaceus*, viz., *D. foliaceus* var. *incisus*.

"From the aspect of this faunule, especially the *Retiograptus* and the branches of *Dicranogr.*, I would place it in the Normanskill or a little younger. In our fauna these two occur only in the Normanskill."

Doctor Kindle refers the two small lots of these remains which he examined to the Upper Ordovician, and Mr. Burling places those which he examined and which were associated with the graptolites to the Normanskill.

Of the Silurian remains the Stomatoporoids were sent to Prof. W. A. Parks, of Toronto University, and the remaining forms were examined by Doctor Kindle. Professor Parks refers all the specimens to the Silurian, and finds that with one exception they all belong to the genus *Chathrodictyon*, the exception belonging to the genus *Labechia*. The remainder of the large collection of Silurian fossils examined by Doctor Kindle were referred by him partly to the Middle and partly to the Late Silurian.

Of the Devonian fossils collected in 1911, Doctor Kindle states:

"The fauna suggests a Middle Devonian horizon and probably includes beds ranging in age from late Onondaga to Portage time. There appears to be no doubt that this fauna is identical with the Devonian fauna, which was found by Kindle³⁷ in the Salmontrout limestone on Porcupine River."

³⁶ Detailed descriptions of these fossils, as well as of all the other fossils collected by the writer along the 141st meridian, will be published in his report on this work, which is in course of preparation.

³⁷ E. M. Kindle: Geologic reconnaissance of the Porcupine Valley, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 327-329.

Concerning the fossils collected from these limestones farther south, Doctor Kindle states:

"The Devonian collection includes two lots which may represent a formation distinct from the Salmontrout limestone. They appear to belong in a Middle Devonian horizon, but the absence from these lots of any species tying them to the others indicates the propriety of provisionally treating them as possibly belonging to a distinct formation."

It thus appears that the Devonian limestones in this section include the Salmontrout limestone, which name is thus, as before mentioned, not sufficiently comprehensive to include all the Devonian limestones along the boundary.

Devono-Ordovician Shale—Chert series.—This series, as shown on the accompanying table of formations, includes beds ranging in age from Devonian to Ordovician. Along Harrington Creek, where these beds have a thickness of at least 300 feet, they directly overlie Devonian limestones, and are in turn overlain by a Carboniferous shale series. Farther south, however, this series is at least 600 feet in thickness, and includes Devonian, Silurian, and Ordovician members. There these beds directly overlie Ordovician limestones, and are in turn overlain by Carboniferous shales and by the Nation River conglomerates, sandstones, and shales. Thus toward the south the shale-chert series gradually replaces, in a time sense, the limestone-dolomite beds.

This series consists dominantly of shales and cherts, and in places thinly bedded, dark gray to black cherts are closely interbedded with gray to black or bluish black, soft, friable shales. The cherts are prevailingly in beds ranging in thickness from 1 to 6 inches, but are in places more thinly bedded; occasionally, however, they are as much as 12 inches thick. The shales are typically very thinly bedded, and with the cherts constitute the most characteristic, prominent, and extensive part of this chert-shale series. Occasional red shales also occur locally intercalated with the darker shales and cherts. Hard, gray, quartzitic shales are also somewhat extensively developed, and in places these contain sufficient iron to produce, when oxidized, a bright red to yellow coloration on weathered surfaces, but only rarely are these rocks red on a fresh fracture. These reddish beds decompose readily to form a red or yellowish sand or mud, which is a very noticeable feature of many of the hillsides on which vegetation is lacking. Hills on which members of this shale-chert series outcrop are thus generally brightly colored and characterized by well rounded forms and gentle slopes. The black, grayish, yellowish, and red beds, with their oxidation products, present a striking, variegated landscape,

the red exposures constituting distinctive landmarks easily recognizable for 10 or 20 miles or even greater distances.

Shales and cherts similar to certain members of this series are exposed on Calico Bluff, facing Yukon River, and there underlie Carboniferous beds of the Calico Bluff formation. These shales and cherts on Calico Bluff have been provisionally assigned to the Upper Devonian on paleontological, stratigraphical, and lithological grounds,³⁸ and in all probability they belong to that age, but as yet perfectly conclusive proof of this is lacking. The Calico Bluff shales and cherts were, however, traced eastward to the boundary line and definitely correlated with members of the shale-chert series there, which is overlain by Carboniferous shales, sandstones, and conglomerates.

Carboniferous—General.—The rock formations of known Carboniferous age, developed along the 141st meridian between Porcupine and Yukon rivers, are here considered under three divisions or as belonging to three formations. In addition, a peculiar conglomerate occurs in one locality, which resembles a consolidated boulder clay, and which is probably also of Carboniferous or Permo-Carboniferous age. The three main Carboniferous formations are the Racquet group, the Nation River formation, and a shale series. The Racquet group, which is developed only in the northern portion of the belt along the Alaska-Yukon boundary here being considered, is composed dominantly of limestone, with some shales, chert and chert conglomerates, and contains both Pennsylvanian and Mississippian fossils. In the southern end of the district a series of conglomerates, sandstones, and shales occurs, which has been correlated with the Nation River formation, and is apparently the stratigraphical equivalent of the lower portion of the Orange group to the north. These beds overlie a series of shales and thinly bedded limestones which contain Carboniferous fossils and possibly include the Calico Bluff formation. The members of the Racquet group in the north appear to be the stratigraphical equivalents of the shale series in the south, and at one point in the vicinity of Ettrain Creek there was noted to occur what appears to be a transition from the dominantly calcareous members of the Racquet group to the more arenaceous and argillaceous sediments of the southern portion of the district.

Shale series.—This formation appears to be about 800 or 900 feet in thickness, and consists dominantly of shales, cherts, and thinly bedded limestones, but includes as well occasional more arenaceous beds that resemble finely textured, calcareous sandstones. The shales range in color from gray to black and are dominantly soft and friable. The cherts con-

³⁸ A. H. Brooks and E. M. Kindle: Bull. Geol. Soc. Am., vol. 19, Oct., 1908, pp. 286-291.

stitute a much smaller proportion of the formation than the shales, and occur prevailing in beds less than one inch thick, but are in places as much as 3 inches or even more in thickness. The limestones characteristically occur in beds having a thickness of less than one foot.

The Carboniferous invertebrate remains from these shale beds along the boundary, as well as from some of the upper members of the Racquet group, were sent to Dr. George H. Girty, of the United States Geological Survey, who has reported on them, and has assigned them all to the same horizon, showing that they are stratigraphical equivalents, as described in more detail further on in this paper. Doctor Girty reports concerning these fossils as follows:

"This group of collections contains types so similar to Russian species described by Tschernyschew in his monograph on Gschelian Brachiopoda that it seems almost inevitable to correlate them at least provisionally with the Gschelian stage, which occurs just below the Lower Permian (Artinskian) of the Russian section. This is true of both groups of collections, though they show fairly distinct facies from one another, for both are about equally related to the Gschelian, yet herein enters an element of doubt, owing to the singular fact that among Tschernyschew's Gschelian brachiopoda, and, indeed, in the associated fauna, are numerous species which not only lack corresponding types in our own Pennsylvanian, but are closely related to types which seem to be restricted to the Mississippian. Some of the collections contain few, if any, of these types, whereas others contain a considerable number of them, and the question is immediately raised whether we are to rely upon the one set of affinities and call the horizon Gschelian or on the other and call the horizon Mississippian. Since, however, we have in Alaska a Lower Carboniferous horizon equivalent to the *Productus giganteus* zone of Europe, to which the present fauna does not appear to be closely related, it seems more probable all should be correlated with the Gschelian.

"I should perhaps add that in the case of all these identifications and correlations I have met not only the usual difficulty, that many of the fossils are poorly preserved so that their identification, and consequently their significance, is doubtful, but also the additional one that I have been entirely without specimens of the Gschelian fauna with which to make comparison and have had to rely solely upon descriptions and figures, chiefly the latter, as the text is mostly in Russian."

Racquet group.—The members of the Racquet group are nowhere very extensively developed within the belt along the Alaska-Yukon boundary, which is here being considered. In the northern portion of the area, however, they occur associated with the older limestones and dolomites, and are in places difficult to distinguish lithologically from the limestones of the Devonian or even earlier Paleozoic periods. This series has an aggregate thickness of at least 1,500 feet, and consists mainly of limestones and cherts, but includes also occasional beds of shale, calcareous sandstone,

and cherty conglomerate. The limestone beds are generally quite crystalline, and range from nearly white through various shades of gray to almost black in color; on fresh fractures, however, these rocks are typically dark bluish gray to nearly black. The upper limestone beds in places contain chert pebbles which are sufficiently abundant locally to constitute typical cherty conglomerates. The chert pebbles are well rounded and usually about the size of marbles, but some were noted as large as $1\frac{1}{2}$ to 2 inches in diameter. In color most of the pebbles are some shade of gray, but occasional black individuals were noted. In places, also, thin beds of chert, similar in appearance to the pebbles, occur intercalated with the limestones, and particularly in the vicinity of Ettrain Creek the formation is characteristically composed of closely interbedded limestones and cherts, the limestone beds ranging in most places from 4 to 12 inches in thickness, and the chert beds being dark gray to almost black in color and ranging in thickness from 2 to 6 inches. In the vicinity of Ettrain Creek, also, this series contains intercalated beds of fossiliferous calcareous sandstone, which apparently indicates a transition there between the typically calcareous Carboniferous beds of the north and the more arenaceous and argillaceous Carboniferous members farther south.

A number of fossils were collected from these beds in the northern portion of the district where this group is most prominently developed. These have been reported on by Doctor Girty, who considers them to be partly of Pennsylvanian and partly of Upper Mississippian age.

The name Racquet group was first applied in the writer's report on the previous season's work along the boundary,³⁹ and was intended to include all the somewhat massive dominantly calcareous Carboniferous beds of that district. Limestones, cherts, cherty conglomerates, and breccias that lithologically very closely resemble the members of the Racquet group are extensively developed on Macmillan River.⁴⁰ The Racquet group is also probably included in the Braeburn limestones, which are extensively developed in Yukon⁴¹ and northern British Columbia,⁴² and are dominantly of Carboniferous age, but may include also Devonian members. This group also corresponds lithologically with portions at least of the Lower C  che Creek group⁴³ of British Columbia and Yukon, which, however, has

³⁹ D. D. Cairnes: Geol. Surv., Canada, Sum. Rept., 1911, pp. 30, 31.

⁴⁰ R. G. McConnell: Ann. Rept., Geol. Surv. of Canada, vol. xv, 1902, pp. 31A-34A.

⁴¹ D. D. Cairnes: Preliminary memoir on the Lewes and Nordenski  ld Rivers coal district. Geol. Surv., Canada, Memoir No. 5, 1910, pp. 28, 29.

⁴² D. D. Cairnes: Portions of Atlin district, British Columbia, with special reference to lode mining. Geol. Surv., Canada, Memoir No. 27, 1912, pp. 53-54.

⁴³ G. M. Dawson: Ann. Rept., Geol. Surv. of Canada, vol. vii, 1894, pp. 37B-48B.

J. C. Gwillim: Ann. Rept., Geol. Surv. of Canada, vol. xii, 1899, pp. 16B-18B.

D. D. Cairnes: A portion of Conrad and Whitehorse mining districts, Yukon. Geol. Surv., Canada, 1908, pp. 25-29.

not been very definitely defined paleontologically, but from the fossils that have been reported it would appear that the Lower C  che Creek group includes the Racquet group.

Nation River formation.—A series of beds which have been tentatively correlated with the Nation River formation extend along the boundary line more or less persistently for a distance of about 9 miles in the vicinity of Yukon River between Tatonduk River and Eagle Creek. This formation consists dominantly of conglomerates, sandstones, and shales, and has a thickness of at least 4,000 feet. The pebbles in the conglomerate beds are composed dominantly of chert, and range in most places from about 1/32 of an inch to 1 inch in diameter. The sandstones are characteristically grayish to brownish, medium textured, hard, firm rocks, which weather in most places to a brownish color; occasional yellowish or reddish appearing beds, however, occur. The shales are prevailingly grayish to yellowish in color and dominantly argillaceous in composition.

The lowest member of this formation on McCann hill is a massive conglomerate bed about 60 feet in thickness. Overlying this basal conglomerate are about 230 feet of brownish to nearly black sandstones of the same composition dominantly as the conglomerate, but in a finer state of comminution. These sandstones are followed by a second conglomerate bed 25 to 30 feet thick, which is in turn overlain by sandstones, shales, and occasional intercalated conglomerate beds. These two lower conglomerate beds appear to be quite persistent and characterize the bottom of the formation along the boundary.

These beds appear undoubtedly to belong to the Nation River formation⁴⁴ of Alaska, which is considered to be of Carboniferous and probably of Pennsylvanian age. This formation along Nation River near the Yukon, where it is most typically exposed, corresponds very closely lithologically with these beds along the boundary, and occupies a corresponding stratigraphical position. In both localities, also, the beds characteristically contain abundant plant remains.

Permo-Carboniferous (?) conglomerate.—Possibly consolidated boulder clay.—On the extreme western edge of the belt under consideration along the Yukon-Alaska boundary line, and just north of Tatonduk River, a peculiar conglomerate is developed. This extends over an area only about one mile in diameter within the mapped area, but was seen to have a more extensive development to the west.

This conglomerate is at least 700 or 800 feet in thickness, and consists dominantly of a firm, somewhat dense, finely textured, reddish, argilla-

⁴⁴ A. H. Brooks and E. M. Kindle: Paleozoic and associated rocks of the Upper Yukon, Alaska. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 294, 295.

ceous matrix, in which are imbedded angular to subangular pebbles and boulders ranging in size from microscopic to 3 or 4 feet in diameter. The matrix appears to have approximately the composition of a boulder-clay, and the greater number of the pebbles and boulders are composed of limestone or dolomite, but some were noted that were composed of other sediments, such as sandstone, conglomerate, and shale.

The prevailing red color of the matrix is due mainly at least to the considerable amount of iron contained in the matrix, which has in places the general appearance of a hematite ore. The conglomerate, where exposed on a small tributary of Tatonduk River, is quite unstratified and has the general appearance of a consolidated and iron-stained boulder-clay. The pebbles and boulders are irregularly distributed and are often quite isolated and completely surrounded by the matrix instead of resting on one another, as in the case of a shore conglomerate.

This conglomerate is thus undoubtedly of terrestrial origin, the term terrestrial being used to imply deposition on the land in contrast to deposition in the sea or on the seashore. Land deposits may, however, be formed in numerous ways, mainly by the action of lakes, rivers, winds, glaciers, and volcanoes, as well as by weathering, creepage, or sliding. Of these, considering the thickness of this conglomerate, its unstratified condition, and the irregular distribution, composition, angularity, and size of the pebbles and boulders, the only two modes of origin which appear to at all satisfy the field observations are glacial action and creepage or sliding.

In general composition this conglomerate appears to much more resemble a boulder-clay than it does slide material, but, on the other hand, its prevailing reddish color and the fact that this conglomerate has not been previously described as occurring in Yukon or Alaska, so far as the writer is aware, and is thus probably not very extensive, would tend to disprove the glacial theory of origin. Also no striated pebbles were found; this may, however, be due to the fact that since the pebbles are dominantly composed of soft materials, such as limestones and dolomites, the scratches, even if they ever existed, might readily have become obliterated. Further, due to peculiar circumstances, the writer was able to examine this conglomerate in only one very limited area and could devote but a few hours to the examination; thus striated pebbles may well occur and not have been found. Pebbles having faceted surfaces, much resembling "soled" pebbles, were, however, noted to be somewhat plentiful. Due to its prevailing color, also, this conglomerate could be seen to extend for several miles to the west of the area examined, showing it to be somewhat extensive for slide material. This, taken in conjunction with the



FIGURE 1.—TYPICAL ANGULAR QUARTZITE TALUS.
This talus is on slopes of characteristic small rounded knoll composed of these rocks



FIGURE 2.—TYPICAL SHALE EXPOSURES
The hills composed of these rocks have dominantly gentle slopes, the rocks being exposed, as a rule, only at or near the summits

thickness of the conglomerate, rather favors the glacier theory. Thus, until more evidence has been obtained, the origin of this conglomerate must remain an open question.

This conglomerate overlies the Devono-Cambrian limestone-dolomite beds and appears also to overlie the Carboniferous shales and cherts, but of this the evidence is not conclusive. The conglomerate was thus probably formed about Carboniferous time, and may correspond to the Permo-Carboniferous tillites or conglomerates, considered to be of glacial origin, that occur in South Africa, Australia, India, and other parts of the world.⁴⁵

Mesozoic-Pennsylvanian—Orange group.—The members of the Orange group are the most extensively developed rocks along the 141st meridian between Yukon and Porcupine rivers. The most northerly exposure of these beds within this belt occurs about 13 miles south of the Porcupine, and thence they occur more or less persistently to Yukon River. Within the portion of this distance from Rat Creek, at about latitude $66^{\circ} 45'$, to 3 miles south of Ettrain Creek, at latitude approximately $66^{\circ} 23'$, a distance of about 95 miles, the beds constitute the prevailing rock exposures.

This group of rocks consists chiefly of shales, sandstones, conglomerates, slates, phyllites and quartzites, but also includes occasional beds of limestone which contain Upper Carboniferous fossils, and are limited to the lower portion of the formation. All gradations occur from only slightly altered shales and sandstones to much metamorphosed slates, phyllites, and quartzites; in fact, almost every type and variety of normal argillaceous and arenaceous sediment is represented, and all are so intimately associated and pass so gradually from one phase to another that in the field it was found necessary to consider them all as a geological unit.

On account of the general paucity of outcrops and owing also to the metamorphosed condition of the beds in places, no complete section of the Orange group was measured at any one point, although partial sections were measured in several places. Also nowhere was any consolidated geological formation found overlying these rocks, so that it is uncertain whether or not the uppermost member of this group was seen. Consequently it is not at all definitely known what aggregate thickness the beds have, but the group is at least 6,000 feet thick and may be nearer twice this amount.

⁴⁵ A. P. Coleman: Glacial periods and their bearing on geological theory. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 349-353.

F. H. Hatch and G. S. Corstorphine: The geology of South Africa. London, 1905, pp. 199-210.

A. W. Rogers: An introduction to the geology of Cape Colony. 1905, pp. 147-179.

Fossils are of rather rare occurrence in all but the limestone members of this group, which are highly fossiliferous. Fossil remains were, however, collected from the shale, sandstone, and quartzite beds at a number of widely separated points. All the Mesozoic remains that were obtained have been examined by Dr. T. W. Stanton, of the United States Geological Survey, who considers most of them to be characteristic of the Lower Cretaceous. Concerning one rather large but imperfect lot, he is, however, able to state only that "my judgment is that these fossils are not older than Mesozoic and that they may be Cretaceous." The Orange group is thus considered as being dominantly Mesozoic, but includes as well certain Upper Carboniferous argillaceous, arenaceous, and calcareous members which contain fossils that are of Permian or Upper Pennsylvanian age. These beds overlie the members of the Racquet group, in which Mississippian and Pennsylvanian fossils occur.

The Mesozoic members of the Orange group of sediments correspond somewhat closely lithologically and stratigraphically with those of the Laberge series,⁴⁶ which extensively developed in Yukon⁴⁷ and northern British Columbia, and particularly resemble these beds in Atlin district,⁴⁸ British Columbia, where they are locally much metamorphosed and altered into slates, quartzites, and related rock types. The members of the Laberge series are considered to be mainly at least of Lower Cretaceous or Jurassic age and classed provisionally as Jura-Cretaceous. On account of the distinctive appearance of certain of the members of the Orange group, especially the banded red and green slates, these are thought in all probability to correspond stratigraphically with certain beds occurring on the MacMillan and Upper Stewart rivers, which have been described by both Mr. R. G. McConnell⁴⁹ and Mr. Joseph Keele,⁵⁰ of the Canadian Geological Survey. Mr. Keele found Triassic fossils in or immediately below these rocks, which appear to correspond to the members of the Orange group.

Quaternary—Superficial deposits.—Under "Superficial deposits" the writer means to include all the Pleistocene and Recent sedimentary de-

⁴⁶ D. D. Cairnes: Preliminary memoir on the Lewes and Nordenskiöld Rivers coal district, Yukon Territory. Geol. Surv. of Canada, Memoir No. 5, 1910, pp. 30-35.

⁴⁷ D. D. Cairnes: Wheaton district, Yukon Territory. Geol. Surv. of Canada, Memoir No. 31, 1912, pp. 53-57.

⁴⁸ D. D. Cairnes: Portions of Atlin district, British Columbia, with special reference to lode mining. Geol. Surv. of Canada, Memoir No. 37, 1912, pp. 59-63.

⁴⁹ R. G. McConnell: The MacMillan River, Yukon district. Geol. Surv. of Canada, Ann. Rept., vol. xv, 1902-1903, pp. 31A-34.

⁵⁰ Joseph Keele: The Upper Stewart River region, Yukon. Geol. Surv. of Canada, vol. xvi, 1904, pp. 13C-18C.

A reconnaissance across the Mackenzie Mountains on the Pelly, Ross, and Gravel rivers, Yukon and Northwest territories. Geol. Surv. of Canada, No. 1097, 1910, pp. 33-36, 39-40.



FIGURE 1.—TYPICAL EXPOSURE OF SHALES OF THE ORANGE GROUP ON KANDIK RIVER



FIGURE 2.—TYPICAL TOPOGRAPHY WHERE THE BED ROCK IS DOMINANTLY COMPOSED OF THE MESOZOIC MEMBERS

MESOZOIC BEDS, KANDIK RIVER

posits and accumulations. These include chiefly gravels, sands, clays, muck, peat, soil, and ground-ice, which floor all the principal valleys of the district and constitute a thin mantle overlying the consolidated rock formations throughout the greater part of the district, particularly in the less rugged localities.

IGNEOUS ROCKS

The igneous rocks of this belt are divisible into two main groups. The one group is composed of somewhat basic intrusives, dominantly diabases, diorites, andesites, and related types; the other group includes mainly plutonic rocks of granitic habit and more acid composition, and are mainly syenites, grano-diorites, and related rocks.

The more acidic group of these rocks were noted in only three or four localities and the exposures are all small. All these rocks cut the members of the Orange group and are thus of Mesozoic or later age. All the members of the more basic group that were examined proved to be diabases, diorites, or andesites. The diabases occur mainly associated with the members of the Tindir group and are in places extensively developed, occurring as dikes, sills, and irregular intrusive masses in the Tindir sediments. Occasional diabase dikes also pierce the overlying beds, and some were noted cutting the Mesozoic sediments. Since the diabase is so extensively developed in association with the Tindir members, however, and but rarely cut the more recent rocks, it is apparent that the diabase in this belt, although lithologically all very similar, ranges in age from Lower Cambrian or pre-Cambrian to Mesozoic or later, but that it belongs dominantly to the pre-Middle Cambrian.

SUMMARY AND CONCLUSIONS

A very complete and interesting section of the Paleozoic has been found to occur along this portion of the Yukon-Alaska boundary, which adds considerable, both stratigraphically and lithologically, to our knowledge of this era in the northwestern portion of the continent. One of the most important results of this work along the boundary is the finding of the great thicknesses of limestones and dolomites which there occur. These beds range in age from Carboniferous down to the Middle and possibly also include the Lower Cambrian, showing that the deep sea reigned, apparently continuously, over extensive portions of the region during this tremendous period of time. Another very interesting conclusion concerns the rapidity with which it has been shown that the lithology changes, and consequently how uncertain and unsatisfactory lithological evidence has proved to be, thus adding greatly to the difficulties connected with geo-

logical mapping in that region. Toward the southern end of the section, where a limestone and a shale group are well developed, at one point the limestone group persists upward from Middle Cambrian to Lower Devonian, and is overlain by the shale group, which there contains Upper Devonian and Carboniferous fossils. Within a distance of 10 miles the same two formations, having changed but slightly lithologically, have altered their relations stratigraphically to the extent that there the limestone group persists upward from the Middle Cambrian only to the Lower Ordovician and is overlain by the shale group, which contains a fauna ranging in age from Upper Ordovician to Carboniferous.

In addition, a certain amount of light has been thrown on the age of the older schistose rocks of the region. Heretofore these rocks, which have been generally considered to constitute the oldest geological terrane in each district in which they have been studied, were accordingly variously classed as pre-Devonian, pre-Silurian, or pre-Ordovician, according to the age or supposed age of the oldest overlying sediments. It would now appear that this schistose complex of the Upper Yukon basin is at least pre-Middle Cambrian and is in all probability of pre-Cambrian age. This information is of more than ordinary significance, since these rocks are so extensively developed, and since from them has been derived a great portion at least of the placer gold of Yukon and Alaska.

In conclusion, the writer wishes to state that the work performed along the 141st meridian, as a result of which this paper was prepared, was necessarily very rapidly performed, owing to the inaccessibility of the district. Consequently the information obtained concerning many points is very incomplete, and numerous interesting problems which might otherwise have been solved still remain unsettled; in fact, the whole work was really that of the pioneer. It is hoped, however, that the knowledge gained will be of some slight assistance in the advance of geological research in this Northland.

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CONTENTS

	Pages
Age of the Don River Glacial Deposits, Toronto, Ontario. By G. Frederick Wright - - - - -	205-214
Evidence of a Glacial Dam in the Allegheny River Between War- ren, Pennsylvania, and Tionesta. By G. Frederick Wright -	215-218
Pleistocene Marine Submergence of the Connecticut and Hudson Valleys. By Herman L. Fairchild - - - - -	219-242
Magmatic Differentiation and Assimilation in the Adirondack Region. By William J. Miller - - - - -	243-264
Characteristics of a Corrosion Conglomerate. By Frederick W. Sardeson - - - - -	265-276

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AGE OF THE DON RIVER GLACIAL DEPOSITS, TORONTO,
ONTARIO ¹

BY G. FREDERICK WRIGHT

(Presented by title before the Society January 1, 1914)

CONTENTS

	Page
Introduction.....	205
Statement of facts as to date and duration of Lake Warren.....	205
Age of Lake Iroquois.....	207
Origin of the warm species of plants and animals in the Don beds.....	210
The Labrador later than the Keewatin glacier.....	212
Summary.....	213

INTRODUCTION

After a preliminary statement of the main facts, the discussion in this paper will relate (1) to the age of the latest glacial deposits at Toronto connected with the existence of the glacial Lake Iroquois, and (2) to the earliest interglacial deposits containing animals and plants which are characteristic of a warmer climate than that which prevails even now north of Lake Ontario.

STATEMENT OF FACTS AS TO DATE AND DURATION OF LAKE WARREN

The occurrence of warm species of plants and animals in interglacial deposits in the Don River Valley, near Toronto, Ontario, seems at first sight an absolute demonstration of an immense interval of time between the two invasions of glacial ice which are there clearly indicated. Briefly stated, the facts are that in the valley of the Don River and at Scarboro heights near Toronto there is at the base a deposit of till which, after having been extensively eroded, was covered by sedimentary deposits of glacial origin 150 feet in thickness which had been brought into standing water by the stream to form a delta whose base extended 25 or 30 miles along the shore. The lower strata of this delta deposit are 35 feet below the present level of the lake and probably at about the same relative level

¹ Manuscript received by the Secretary of the Society February 17, 1914.

as when laid down. But the water from some unknown cause rose as the accumulation progressed until it was 150 feet higher than now, when the upper sediments of coarser gravel were deposited; then the water began to fall and a period of erosion succeeded.

This proceeded until at Scarboro a V-shaped channel, one mile wide at the top and 150 feet deep, was worn in the sedimentary deposits, whereupon the ice advanced again and covered the whole with sheets of boulder-clay and assorted rubble drift to a total depth of 200 feet. Here certainly seems to be an interglacial deposit of unusual extent.

Nor is the character of the fossil plants and animals included in the interglacial deposits any less noteworthy. Both the fauna and the flora of the lower, or Don, beds indicate a much warmer climate than those of

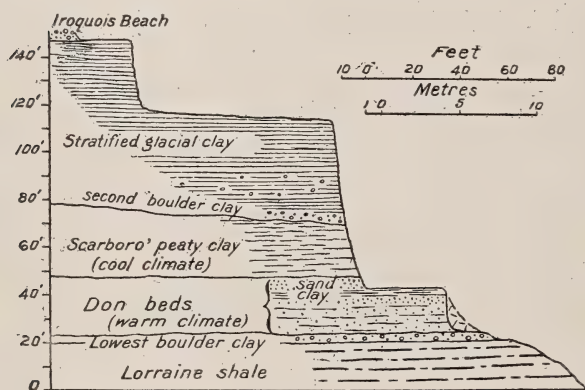


FIGURE 1.—Section of Don Valley Brickyard, Toronto (Coleman)

the upper, or Scarboro, beds. In the Don beds there are found leaves and wood of maple, elm, ash, hickory, basswood, and even of pawpaw and osage orange, which now flourish only in latitudes several degrees south of Toronto; also, of the mollusks found in the Don beds, four of the

species are not now found in the Saint Lawrence basin, but only after passing the watershed which separates it from that of the Mississippi.

On the other hand, the upper, or Scarboro, sands and clays are wanting in the species indicating a warmer climate, but abound in both a flora and a fauna suggestive of Labrador and of the region north of Lake Superior.²

In the opinion of Professor Coleman, these facts can not be accounted for except on the supposition that the earlier ice-sheet retired from practically the whole region to the northward before the latter one began its advance, which certainly looks very reasonable at first sight. But there are a number of considerations, too much overlooked, which seem to compel, or at least to permit, a contrary conclusion.

² Coleman: "Glacial and interglacial beds near Toronto," *Journal of Geology*, vol. 9, pp. 285-310. "Lake Iroquois and its predecessors at Toronto," *Bull. Geol. Soc. Am.*, vol. 10, 165-176. "On the Pleistocene near Toronto," *British Assoc. for Adv. of Sci.*, Report 1900, pp. 328-334; *Guide Book*, No. 6, for International Geological Congress, pp. 10-34.

AGE OF LAKE IROQUOIS

Beginning with the age of the upper shelf worn in the deposits at Toronto, approximately about 200 feet above the level of Lake Ontario, it is to be noted as bearing on the subject:

1. That it is younger by several thousand years than the beaches of glacial origin about the south end of Lake Michigan and than those formed on the shores of Lake Warren on the south side of Lake Erie. No one will question the statement that the final retreat of glacial ice from the United States and Canada proceeded from the southwest, uncovering successively the western areas of the Great Lakes, until finally the ice barriers to the east over central New York and Quebec gave away and



FIGURE 2.—Map showing Stages of Recession of the North American Ice-sheet (Upham)

permitted the drainage of the Great Lakes to pursue its present outlet (see map on opposite page). But for a considerable period there was a drainage leading to the Hudson Valley at a higher level along the ice-front through the valley of the Mohawk River in central New York. Whatever age, therefore, we assign to the erosion of the 200-foot shelf at Toronto, the shorelines at the south of Lake Michigan and those of Lake Warren in Ohio must be much older.

2. But we are compelled to set moderate limits to the time which has elapsed since the ice withdrew from the southern end of Lake Michigan.

a. The dunes at the south end of Lake Michigan represent accumulations which have been going on ever since the ice withdrew from that region. They are composed of sand, which is borne along by the waves and currents on the west shore of the lake and is finally caught up by

the winds to form the dunes which attract the attention of all passengers on the railroad going to Chicago from the east. From the amount of these accumulations and from the rate at which the sand is now known to be moving past Chicago along the west side of the lake toward the south end of it, from 10,000 to 15,000 years is more than ample time to account for the accumulation of the entire mass of the dunes.

b. The waves of Lake Michigan are constantly eating into the west shore at a rate which, according to the most moderate computations, would produce the 70-foot shelf extending out to deep water in less time than that already allowed for the accumulation of the dunes.³

3. The latest glacial deposits on the south side of Lake Erie are found in the beaches that mark the shoreline of Lake Warren, the highest of which is approximately 200 feet above Lake Erie in Ohio. These beaches, I think I have proved conclusively, can not be more than 10,000 or 12,000 years old. The evidence exists in the small amount of erosion that has been accomplished by the streams of northern Ohio, which have been flowing into the Lake Erie basin ever since the retreat of the ice from that region. In particular, attention is directed to the small extent to which Plum Creek, in Oberlin, Ohio, has enlarged its trough. This trough is 50 feet above the highest Lake Warren beach, and only five miles distant, is entirely in glacial deposits, with no rock obstruction, yet it is so narrow and shallow that any calculations making it much more than 12,000 years old, and especially those that make it several multiples of 12,000, involve an absurdly low rate of erosion. Moreover, data have been collected from the present eroding efficiency of the stream which give results well within the above figures.⁴

4. A clue to the length of time during which Lake Warren continued to cover the bordering land on the south side of Lake Erie is furnished by deposits recently uncovered by excavations at Fremont, Ohio. The sedimentary plain on which the city of Fremont is built lies below the 100-foot level of the lowest shoreline of Lake Warren. The sedimentary deposits consist of the material brought into Lake Erie by Sandusky River, which is spread out as a delta. The depth of these lacustrine beds is at least 25 feet. The thickness of the laminae, according to my measurements made in several excavations, is on an average one-seventh of an inch, making 84 to the foot, making a total of 2,100, which would be the number of years required for the accumulation on the supposition that

³ See the paper of Dr. Edmund Andrews in *Transactions of the Chicago Academy of Sciences*, vol. ii, 1870, pp. 1-23. This and the later facts bearing on the question are fairly and fully discussed by Leverett in *Monograph xxxviii* of the U. S. Geol. Survey, pp. 453-459.

⁴ See Wright's "Ice Age in North America," 5th ed., pp. 564-568; also *Bull. Geol. Soc. Am.*, vol. 23, pp. 278-280.

each lamina represented an annual deposit. Whatever be the date, therefore, which we assign to the upper beach of Lake Warren, that of the Iroquois beach around Lake Ontario must be 2,000 years less. This, according to my calculation, would bring the date of the 200-foot shelf at Toronto at about 10,000 years.

5. To account for the high level of the water in Lake Iroquois, which eroded the 200-foot shelf at Toronto, it is sufficient to note that the shelf has almost exactly the same elevation as that of the col from the Ontario basin into the Mohawk Valley at Rome, New York. Lake Ontario is 247 feet above the sea. The col at Rome is 445. Moreover, as Professor Fairchild has abundantly detailed, ice obstructions in the Mohawk Valley raised the level of the drainage lines into the Mohawk Valley for an indefinite period.⁵ One of the clearest evidences of this exists a few miles southeast of Syracuse, where a stream comparable in size to that of Niagara, but in fact doubtless much larger, has eroded a rock gorge of such length and proportions that its formation must have occupied many centuries. This stream must have been kept up at this level by the ice bordering it on the north side and filling the valley.

6. All these considerations show that there must be some error in the assumptions which underlie the calculations which assign a date of from 20,000 to 40,000 years to the formation of Lake Iroquois, to the erosion of the 200-foot shelf at Toronto, and we may add to the age of the Niagara Gorge. It should be remembered that all these calculations are based on assumptions underlying the interpretation of very complicated phenomena. Among these assumptions the most misleading are those which unduly minimize the rate at which glacial movements and torrential erosion may take place. By way of caution it is sufficient to call attention to two facts:

a. Within 25 years the front of the Muir Glacier, in Alaska, has retreated seven miles, while the ablation from its surface during that time amounts to fully 700 feet, thus confirming my original estimate that since Vancouver's visit in 1794 the glacier has retreated more than 30 miles, and that the ablation of the surface during that time amounts to more than 2,000 feet. This certainly is a movement on a scale sufficiently large to be considered in speculating concerning continental glacial ice-sheets.⁶

b. Dr. Warren Upham in his exploration of the shoreline of Lake Agassiz obtained evidence which is ample to show that the retreat of the ice-front from the Canadian boundary in the Red River of the North so

⁵ See Fairchild: *Bull. Geol. Soc. Am.*, vol. 10, pp. 27-68; "Pleistocene geology of western New York," 20th Rep. of State Geol., 1900, pp. 13-139.

⁶ See Wright's "Ice Age in North America," 5th ed., chap. 3, with references.

as to open the drainage into Hudson Bay did not occupy more than 2,000 years, making the average rate of the retreat of the ice-front one-half mile per annum.⁷ This evidence consists largely in the small extent of the dunes at the south end of Lake Agassiz as compared with that of those at the south end of Lake Michigan, and of the small extent of the deltas formed on the western shore of Lake Agassiz deposited by such streams as the Saskatchewan and the Assiniboin.

So little is known about the cause of the climatic changes which produce and terminate glacial periods that speculation apart from the facts at hand is of little value.

ORIGIN OF THE WARM SPECIES OF PLANTS AND ANIMALS IN THE DON BEDS

The occurrence of warm species of plants and mollusks, referred to, in the Don River Valley takes us back to the earliest stages of the Glacial period, and at first sight seems to prove, as Professor Coleman maintains, that a warm period intervened in that latitude between two successive glacial advances, and implies that the first ice-sheet completely disappeared from North America and was succeeded by a new and independent movement. But when the evidence is closely examined in the light of other well established facts it would appear that such a sweeping inference is by no means necessary.

a. It does not appear that the glacial till below the fluviatile beds in the Don Valley contains any roots of the trees and shrubs supposed to have existed in the inter-Glacial warm period, whereas in front of the Muir Glacier in Alaska my photographs distinctly show such stumps and rootlets projecting from the underlying soil into the fluvial beds that had enveloped them and were subsequently covered over by the glacier's advance.⁸

b. It is entirely possible that the specimens of warm species of plants and animals in the fluvial deposits overlying the lower till were derived from the underlying deposit of late Tertiary age, having been plowed up by a readvance of the ice after a temporary recession and raised without much disturbance to the higher levels, where they are now found. This supposition, which would seem incredible until all the elements involved had been taken into consideration, is rendered easily credible by what has been learned in recent times concerning the deposits of Moel Tryfaen

⁷ See Monograph xxv of U. S. Geol. Survey; Bulletin No. 29, U. S. Geol. Survey; Annual Report, Canadian Geol. Survey, n. s., vol. iv, for 1889, part E. The facts are succinctly stated by Dr. Upham in Wright's "Ice Age in North America," 5th ed., pp. 400-406 and 543-548.

⁸ See Wright's "Ice Age in North America," 5th ed., p. 63.

in Wales, Macclesfield in England, and various other places. In these localities well preserved shells, such as occur in the Irish Sea, were pushed up by the glacial movement from the north to an elevation of more than 1,000 feet, where on the melting of the ice they were redeposited in temporary lacustrine pools and preserved in strata of sand marked by every characteristic of cross-bedding.⁹ While most of these specimens are fragmentary they were by no means all of them so. Professor Kendall reports finding five whole shells in the course of a few hours' search at Moel Tryfaen alone, while Prof. McKenny Hughes reports that some of the specimens are whole, and he personally assured me that he had found in these deposits some shells with both sides held together by the original ligaments. How these shells could have been brought up to these positions without showing signs of abrasion may be explained on the supposition that large compact masses of the sea-bottom were broken up and pushed before the advancing ice, as great masses of chalk have been pushed inland over the east shore of England and over the southern end of Sweden. Professor Holst took me to visit such a mass of chalk a few miles east of Malmö, which was 3 miles long, 1,000 feet wide, and 100 to 200 feet thick, which had glacial deposits both under it and over it. In the case of a frozen or compact mass of soil containing fossils the process of melting would result in waterlaid deposits containing fossils showing even less signs of abrasion than if carried along tumultuously by a running stream for any considerable distance.

All the older geologists interpreted these lacustrine shell beds at Moel Tryfaen and Macclesfield as evidence that the shell-fish had lived and died in that immediate locality, and supposed that to account for them there must have been a subsidence of the British Isles to the extent of more than 1,000 feet, permitting the shells to grow on the ocean bed at the level where they are now found. Among the authorities maintaining this view are to be numbered Darwin, Prestwich, Ramsay, and McKenny Hughes; but at the present time the geologists of Great Britain almost universally regard the deposits as having been formed in the manner described. In the case of the deposits under consideration at Toronto, where there has been scarcely any, if any, elevation of the fossils above their original position to get them where they are now found, it would

⁹ The fullest statement of the evidence bearing on this subject will be found in a communication of Prof. Percy F. Kendall, F. G. S., incorporated in Wright's "Man and the Glacial Period," pp. 137-181; but see also a paper of T. McKenny Hughes, of Cambridge, England, on "The evidences of the later movements of elevation and depression in the British Isles," Victoria Inst., 1880. See especially, however, "Supposed interglacial shell-beds in Shropshire," England, by G. Frederick Wright, in Bull. Geol. Soc. Am., vol. 3, pp. 505-508; and, by the same, "Theory of interglacial submergence in England," in American Journal of Science, vol. xliii, January, 1892, pp. 1-8.

seem unwarranted to draw any sweeping conclusion from their occurrence in the lower part of the fluvial beds overlying the lowest till.



FIGURE 3.—Map of North American Pleistocene Ice-sheet at its maximum Extension

Showing the approximate southern limit of glaciation, the three main centers of ice accumulation, and the driftless area within the glaciated region. (United States Geological Survey.)

THE LABRADOR LATER THAN THE KEEWATIN GLACIER

In discussing inter-Glacial epochs and their time ratios it would seem that too little attention has been paid to the evidence that in America the glacial movement from the Keewatin center preceded that from Labrador. How far east the early movement of the Keewatin ice-sheet extended it is impossible with our present knowledge to tell with certainty; but Lake Superior copper has been found in the glacial deposits in Columbus, Ohio, and still farther north and east in Medina County,

Ohio, and, according to Prof. E. H. Williams, at Warren, in western Pennsylvania, while red jasper conglomerate boulders from north of Lake Huron occur as far east as Ashtabula County, in the extreme north-eastern part of Ohio. It is hardly possible that these materials could have been transported so far east during the later portions of the glacial invasions, for that invasion consisted of Labradorian ice. The so-called Illinoian deposits pushed from the eastward across the State of Illinois, and even extended a short distance into eastern Iowa, where in the vicinity of Keokuk red jasper conglomerate boulders from the north of Lake Huron are found in considerable abundance. It is thus certain that the glacial movement from the Labrador center was later than that from the Keewatin center. For a long distance east of the Mississippi River we know that the deposits of the Labrador ice-sheet overlies those of the Keewatin sheet. It is noticeable also, as already indicated, that the ice departed from the western regions long before it disappeared from New York, New England, and Quebec. The distinct signs of inter-Glacial epochs are only in this western field. No satisfactory evidence of extended inter-Glacial epochs has been found in the eastern regions. As bearing on the larger question of an inter-Glacial epoch covering the whole northern hemisphere, it is also significant that the geologists of Great Britain now maintain that they discover no evidence of such an inter-Glacial epoch in the British Isles, nor do the geologists of Sweden in Scandinavia.¹⁰

I long ago called attention to the fact brought out during the survey of the terminal moraine in Pennsylvania by Professor Lewis and myself that the boundary of the glaciated areas in the central and the eastern part of the United States consists of the arcs of two circles, with their centers respectively in Labrador and the Lake Superior region. The junction of these arcs is at Salamanca, New York, almost exactly on the meridian of Toronto. It is, therefore, a plausible hypothesis that the deposits of Toronto, where these contending ice-fields met, should reveal many abnormal phenomena.

SUMMARY

The following order of events would seem to explain all the facts:

1. First, the Keewatin Glacier pushed southward to the glacial limit in the Mississippi Valley and eastward as far as western Pennsylvania

¹⁰ See Lamplugh's "Presidential address to the geological section of the British Association for the Advancement of Science," at York, 1906; also paper before the International Geological Congress, at Toronto, 1913; also Nils Olof Holst's "Förhistorisk gruf-brytning i Sverige," in which he estimates the close of the Glacial period in Sweden as not more than 7,000 years ago.

and the center of Lake Ontario, extending in the vicinity of Toronto into a region which was occupied by some species of plants and animals which now exist only at a considerable distance to the south. At that time the lower Don beds were deposited.

2. Later the Labrador Glacier pushed outward as the Keewatin Glacier receded, moving, as is shown by the glacial scratches and transportation of boulders nearly east and west in the basins of lakes Ontario and Erie, and pushing on as far as the Mississippi River at Keokuk, Iowa, there indeed crossing the river for a short distance. During this advance over the deserted Keewatin deposits in the vicinity of Toronto the Scarboro beds, overlying the Don beds, were deposited and some of the fossil plants and animals native to the lower beds incorporated into the lower portions of the upper beds. In the early part of this movement the Rome outlet to the Ontario basin was still free from ice and probably at a lower level than now. This was subsequently either filled with ice or gradually elevated so as to account for the rise of the water and the accumulation of the Scarboro beds.

3. On the retreat of the Labrador ice the basin of the upper lakes was uncovered, bringing Lake Warren into existence, while the western boundary of the ice obstructed the drainage to the east. At a later stage this boundary retreated farther east and north, so as to uncover the Rome outlet into the Mohawk Valley, giving rise to Lake Iroquois and allowing for the erosion of the shelf 200 feet above Lake Ontario, now covered by Iroquois sands north of Toronto and Scarboro. The elevation of this Iroquois beach at Toronto corresponds closely to that of the col at Rome.

4. At a later stage the ice retreated so as to open the outlet into the Saint Lawrence.

5. Following this there was the rapid differential rise of land toward the northeast, which elevated the Iroquois beaches toward the north and northeast.

Thus we have brought into order all the complicated facts involved in this most puzzling problem, including those which demonstrate the late date of the shorelines of Lake Warren south of Lake Erie in Ohio. Any supposed sequence of events which fails to account for the late date of these shorelines must involve some error which vitiates the theory. While we have no data from which to draw even approximate conclusions concerning the date of the beginning of the Glacial period, there is nothing which would appear to contradict the opinion of the geologists both of England and Sweden that while the departure of the glacial ice-sheets was very rapid, taking place only a few thousand years ago, the advance was very gradual, occupying an immense period and accompanied by numerous temporary intermissions.



FIGURE 1.—SOUTHERN END OF GLADE RUN TERRACE, 100 FEET ABOVE THE RIVER
Photographed by A. E. Ettinger



FIGURE 2.—GRAVEL PIT IN NORTHERN END OF GLADE RUN TERRACE, 250 FEET ABOVE THE
RIVER
Photographed by A. E. Ettinger

GLACIAL TOPOGRAPHY, GLADE RUN TERRACE, PENNSYLVANIA

EVIDENCE OF A GLACIAL DAM IN THE ALLEGHENY RIVER BETWEEN WARREN, PENNSYLVANIA, AND TIONESTA ¹

BY G. FREDERICK WRIGHT

(Presented by title before the Society January 1, 1914)

CONTENTS

	Page
The observable field data as to upper drainage.....	215
The southern drainage.....	216
Conclusions.....	218

THE OBSERVABLE FIELD DATA AS TO UPPER DRAINAGE

The portion of the Allegheny River Valley between Warren, Pennsylvania, and Tionesta presents some of the most puzzling and important glacial phenomena bearing on the interval of time separating the earliest from the latest advances of glacial ice. The moraine traced by Lewis and Wright here falls several miles short of reaching the Allegheny River at Warren. But older glacial deposits are found several miles south of the Allegheny about the headwaters of Tionesta Creek, at Stoneham and Clarendon. These are evidently waterlaid, and fill a broad valley opening north into the Allegheny about two miles above Warren. The glacial deposits at Clarendon are 308 feet thick. The upper 60 feet consist of gravel containing a noticeable amount of granitic material. This is underlain by 148 feet of sand containing a small amount of gravel. Beneath this there are 100 feet of clay, in which there is an occasional stratum of logs. The rock-bottom at Clarendon is 160 feet below the present level of the Allegheny at Warren. The descent of the rock-floor in this valley is 125 feet in the 12 miles from Sheffield to Warren, while the descent of the rock-floor in the Conewango Valley is 130 feet from Warren to the State line. This would demonstrate that the preglacial drainage was through the Conewango, were it not that at places the rock-bottom of the Allegheny below Warren toward the mouth of Brokenstraw Creek at Irvine is a few feet lower than it is at Warren, and the depth

¹ Manuscript received by the Secretary of the Society February 17, 1914.

of the rock-bottom of the Allegheny below Irvine has not been definitely determined (see the Warren Folio of the United States Geological Survey by Mr. Charles Butts, page 9). Still there can be no reasonable doubt

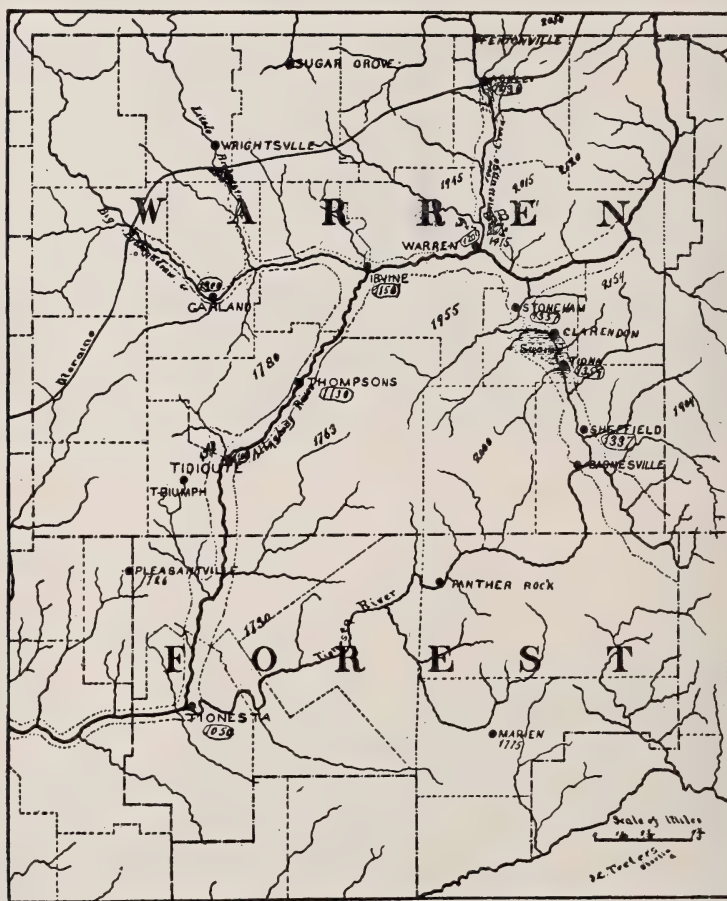


FIGURE 1.—Map of the Vicinity of Warren, Pennsylvania

that the preglacial drainage of the upper part of Tionesta Creek was with that of the neighboring portions of the Allegheny to the north through Conewango Creek.

THE SOUTHERN DRAINAGE

The point, however, on which we need light is: What was the southern line of drainage during the earliest stages of the glacial invasion, when

the northern outlet was obstructed by what would be called Kansan ice? Upon this light is shed by study of the high-level glacial terrace deposits in the Conewango and Allegheny valleys east of Warren.

1. It is evident that the low portion of the High Terrace deposits in East-Warren just above Indian Hollow, as well as the lower portions of the deposits at Clarendon, were in still water, for in both cases they consist of fine sand and blue clay, while the upper portions are of coarse gravel, with occasional pebbles of considerable size, indicating a current of considerable velocity. The elevation of the summit of the gravel terrace in East-Warren is 250 feet above the present level of the river.

2. But most significant of all is the occurrence of a gravel terrace of equal height, beginning at the golf grounds southeast of Warren and running about a mile southeast, up the Allegheny Valley to the mouth of Glade Run, nearly opposite the old northern opening of Tionesta Creek into the Allegheny, and pointing directly to it. This terrace diminishes in height and width toward the southeast, but at its termination contains many large angular rock fragments which must have been brought in by floating ice. It is evident that this was deposited by a powerful stream making for the Tionesta outlet.

3. Concerning the deposits farther south in the Tionesta outlet, Prof. E. H. Williams gives me the following facts:

"The Clarendon gravels are three moraines running north $38^{\circ} 30'$ east. The largest has its crest east of the saddle between Warren and Clarendon, so that a stream which could carry gravel to Clarendon would find a down grade thence through Tiona, Sheffield, Barnes, and the Tionesta River to the Allegheny.

"The above crest is 1,110 feet west of Clarendon station. The second and parallel moraine is the slightest and rises but a few feet above the cranberry bog. It is 100 feet broad and its crest is 660 feet east of the station. It has been used as a road-bed across the bog. The third moraine has its edge 920 feet east of the station. It is 360 feet broad, and its height on the south side of the track is 8, and on the north side 10 feet above the railroad track.

"The material of the greatest (western) moraine is mostly local. The foreign material is but one in from one thousand to ten thousand. The crystallines are like the high level East Warren gravels, and the fossiliferous part like the low level South Warren gravels. The moraines are water-laid. The matrix on the valley sides is a sandy clay, so plastic that it will ball slightly; that in the center has been levitated and is sandy. The crystalline and foreign part is more concentrated in the center; the valley sides are more mixed with slope wash.

"Now, here is the point I wish to make. It is down grade from Clarendon through Tiona and Sheffield to Barnes and thence down the Tionesta. If there were a clear channel from Warren to Clarendon—as the latter is over the saddle from the former—any material delivered by water at Clarendon must

of necessity have been delivered lower down the steep channel at Tiona, Sheffield, Barnes, and along the trough of the Tionesta; but *there are no foreign components in the gravels east of Clarendon.*

"From Tiona eastward the gravels are the same slabby locals with rounded edges that we find in the unglaciated portions of the Kinzua Valley, and every observer has reported no crystallines in the Tionesta Valley except at its immediate debouchment into the Allegheny."

CONCLUSIONS

From these facts it is clear that (*a*) the deepest rock erosion at Warren was preglacial; (*b*) the earliest glacial drainage must have been through the Tionesta outlet rather than down the Allegheny Valley to Tionesta; (*c*) the absence of northern drift material east of Clarendon indicates that the continuance of the glacial stream through the Tionesta was temporary; (*d*) before the northern drift material had proceeded far in filling that valley the drainage was diverted down the Allegheny, which would indicate that for a short period there was an ice-dam below Warren which, on giving way, permitted the diversion to the present channel; and (*e*) it is therefore improbable that there existed at that time a col at Thompsons, as has been surmised.

It is fair, however, to say that Prof. E. H. Williams supposes that all the phenomena can be best accounted for by the supposition that there was at first a col somewhere below Tionesta which impounded the water and raised the level to that of the highest glacial terraces at Warren and Clarendon.

This would seem to render the theory of an ice dam below Warren unnecessary, since it would provide slack water at Warren, Stoneham, and Clarendon long enough to account for the limitation of northern drift to the upper part on the Tionesta Valley. On this supposition the desertion of the Tionesta outlet would be due to the fact that the col at Thompsons had already been worn lower than the level of the moraine between Stoneham and Clarendon. But an examination of the map will show that it is difficult to see why, if the channel at Thompsons had always been open, the swollen glacial current coming down the main channel of the Allegheny should not have pushed past the Tionesta opening and carried its material along the present course of the channel below Warren, instead of down Glade Run toward the Tionesta. In view of the evidence that the ice did actually cross the Allegheny below Warren, the existence of the ice dam supposed seems to give the easiest and, indeed, the only explanation of all the facts connected with the singular distribution of the gravel deposits described in the text.

PLEISTOCENE MARINE SUBMERGENCE OF THE CONNECTICUT AND HUDSON VALLEYS¹

BY HERMAN L. FAIRCHILD

(Presented before the Society December 31, 1913)

CONTENTS

	Page
Introduction.....	220
Historical.....	220
Views of Edward Hitchcock and C. H. Hitchcock.....	220
Work of James D. Dana.....	221
Work of Warren Upham.....	222
Work of B. K. Emerson.....	224
The river theory; difficulties and inconsistencies.....	225
The upper and the lower valley.....	225
Deltas.....	226
Terraces.....	227
Occurrence.....	227
Discordance.....	227
Terraces in the Hudson-Champlain Valley.....	228
Origin.....	229
Detritus.....	229
Character.....	229
Amount.....	230
Disposition.....	231
Lower series of plains.....	231
Meanders; ox-bows.....	232
Kettles.....	232
Marine submergence.....	233
Theoretic plane.....	233
Connecticut Valley references.....	235
Hudson-Champlain Valley references.....	235
Comparison of data.....	238
Phenomena of the summit level.....	239
Glacial deltas.....	241
Features of the lower levels.....	241
Absence of marine fossils.....	242

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INTRODUCTION

Some postglacial submergence of New England has long been recognized, but the amount has not been determined. Recently it has been shown that the marine plane in the Hudson-Champlain Valley rises from zero at New York Bay to about 750 feet on the Canadian boundary.² It is evident that the territory adjacent to the Hudson Valley must have participated in the depression and uplift of the land, and it seems quite certain that the Connecticut Valley, lying parallel with the Hudson-Champlain Valley and only 60 miles distant, should exhibit similar evidences of submergence in oceanic waters.

After reviewing the literature on the Connecticut Valley terraces an examination was made of the valley from Long Island Sound northward to Wells River, Vermont. The uplifted plane of the static waters as determined by Professor Emerson for Massachusetts was taken as the provisional datum, and it was found that this plane when projected north and south throughout the valley coincided, with unexpected precision, with the highest shoreline features. The plane is shown in the diagram, plate 10.

The tilted marine plane in the Connecticut Valley has nearly the same gradient as the corresponding plane in the Hudson Valley, but lies 50 feet higher for the same latitudes. The isobases consequently lie about 20 degrees north of west by 20 degrees south of east.

The elevated terraces on the slopes of the Connecticut and neighboring valleys, which have been attributed to enormous river floods, are really shore deposits, spread out in sealevel waters as the land was slowly lifted out of these waters. The summit plane of these waters, as indicated by scattered beaches and deltas, has not been previously recognized south of Massachusetts, because the phenomena lie higher than the broad terraces, often far back on the valley slopes, and are inconspicuous.

The physical history of the Connecticut Valley, and of all New England, is so radically different from the prevailing river theory that it seems desirable to review the entire problem.

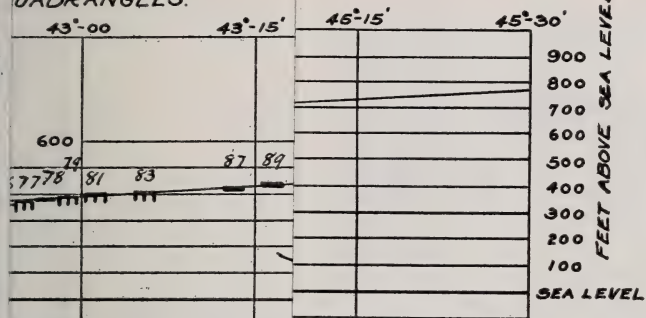
HISTORICAL

VIEWS OF EDWARD HITCHCOCK AND C. H. HITCHCOCK

In the *Geology of Massachusetts, 1841*, Edward Hitchcock speaks of only the lower terraces of the Connecticut Valley, which he attributed to

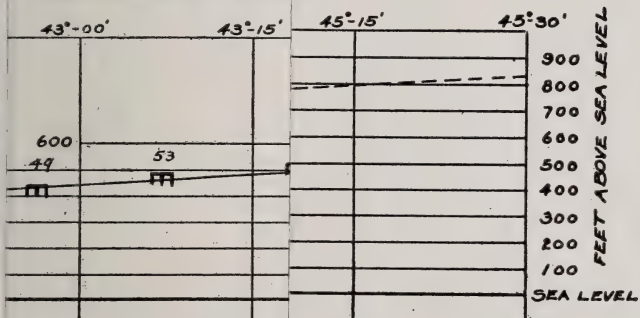
² New York State Museum, Bull. 164, 1913, pp. 23-25. Bull. Geol. Soc. Am., vol. 24, 1913, pp. 157-160.

QUADRANGLES.



STADY SARATOGA GL^{acial} Boundry
ES SCHUYLerville FPA

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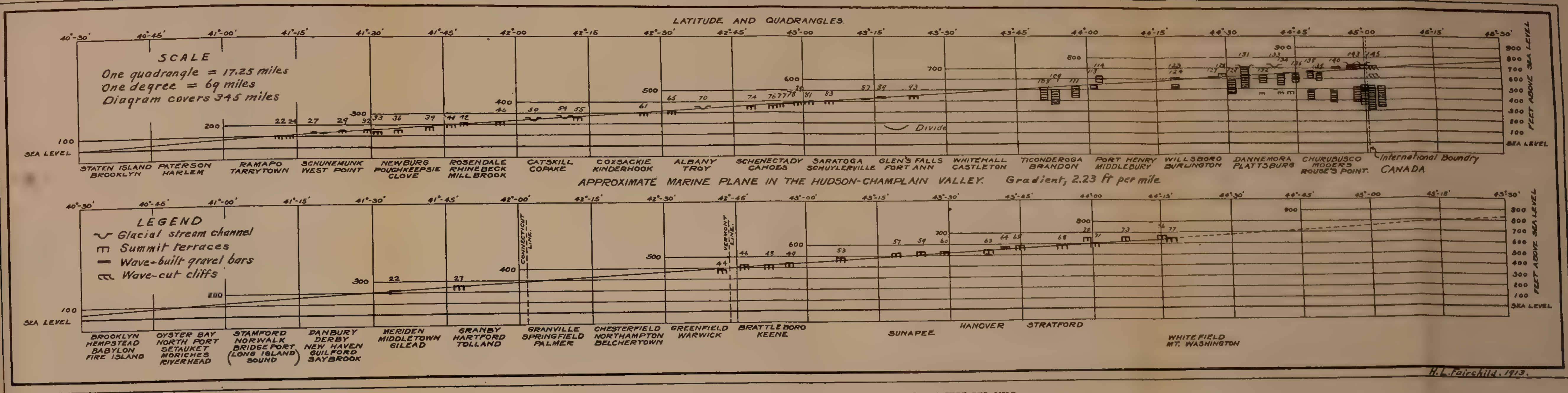


E BORO
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H. L. Fairchild, 1913.

NECTICUT VALLEY. GRAD



1911

to 1911 = 17.25

to 1912 = 6.75

to 1913 = 7.25

1914

to 1914 = 17.25

to 1915 = 6.75

to 1916 = 7.25

to 1917 = 7.25

the work of the river, cutting down through 100 feet to its present inactive condition. He does not discuss the higher terraces nor the deltas at the mouths of tributary valleys.

The *Geology of Vermont*, 1861, gave positive adherence to the iceberg theory of drift origin. New England was supposed to have been deeply submerged in the ocean. Vermont had been buried 5,000 feet in the sea and marine beaches were found up to a present height of 2,196 feet (volume 1, page 183). Evidently the high-level glacial gravels and glacial lake deposits were mistaken for marine features. The terraces of the Connecticut Valley were described and figured by C. H. Hitchcock with considerable detail. They were considered the product of the combined action of the lowering sealevel (and lake) waters with that of river flow. This view was essentially correct; but the upper limit of the static waters was not recognized, because of the belief in deep submergence, and no discrimination was made between the terraces built in standing water and those due wholly to river work.

WORK OF JAMES D. DANA

The earliest important writings on the terraces in the southern part of the Connecticut Valley were made by James D. Dana in his *Manual of Geology*, in the *Transactions of the Connecticut Academy of Science*, volume 2, and chiefly in the *American Journal of Science*. In the early edition of his *Manual*, 1867, he recognized the depression of the land during the "Champlain Epoch," with increase in height of the marine plane toward the north. Elevations were given as follows: 30 to 50 feet in northern Connecticut, 100 to 170 feet in Massachusetts, and 170 to 200 feet in New Hampshire.

In 1873 (in *American Journal of Science*, volume 5, pages 198-211) he expressed the view that the amount of Champlain submergence was about 50 feet on Long Island Sound and greater northward, and that the high valley terraces were river floodplains which "once filled the valley across" to depth of 200 feet. In subsequent papers his estimate of the amount of submergence was less for the shore of the Sound.

Extended writings up to 1876, in volumes 9-12 of the *Journal*, discussed the phenomena in much detail, holding the view that "the ocean took no part in the formation of the river terraces"; "the height of the flood the chief cause of the height of the terraces" (volume 10, page 435). He thought that the river had a depth in glacial flood of 150 feet and a width of 15 miles in the Hartford-Turners Falls section (page 507). The depression of the Connecticut coast he estimated as 15 feet.

The publication by Warren Upham in 1878 of detailed description of

the terraces in the head section of the Connecticut Valley stimulated Dana's critical interest in the study. He made surveys and reviewed Upham's data and published a second series of papers, with detailed description and refined discussion of the phenomena, in the *Journal*, volumes 22-23, in 1881-1882. Dana confirmed Upham's measurements for altitude, but disagreed as to the height of the glacial flood. Upham had taken as the "normal" terraces, representing the summit of the flood waters, the higher of the broad or more extended and continuous terraces, and regarded the deltas or "delta terraces" at the mouths of the side valleys and tributary streams as much above the river level. Dana clearly showed that the high delta terraces were built in waters that must have flooded the whole width of the valley, and that consequently they are the best indication and measure of the full height of the "flood" (volume 23, pages 94-96).

Probably Upham realized the great difficulties involved in admitting a river of sufficient depth and volume to include the high "tributary" delta terraces. Dana was forced to accept the fact in spite of the consequent difficulties, and then proceeded to wrestle with the problems. His subsequent writings on the subject are mostly efforts to harmonize inconsistencies or ingenious explanations of difficulties that were unexplainable under the river theory.

Professor Dana found difficulty in accounting for the source of the immense volume of water to produce and sustain a river of such great size and steep gradient (volume 23, pages 367-372), the fine character of the terrace material, chiefly clay and fine sand, being inconsistent with a stream flow of such volume and velocity (pages 191-194); the necessity of postulating dams in the Connecticut and adjacent valleys in order to check the velocity of the flood (volume 25, pages 440-448); the source of the enormous mass of detritus required to fill the valley to the depth of 200 feet, and the lack of the coarse material that should complement the fine, and particularly the disposition of the detritus derived from excavating the width of the valley to the depth of 200 feet.

The problem of the valley terraces does not appear to have been seriously considered by Dana after 1883. In the *Proceedings of the American Association for the Advancement of Science*, volume 32, page 198, speaking of the New Haven region, he says: "Twenty-five to thirty-five feet is the greatest amount of submergence that the facts sustain."

WORK OF WARREN UPHAM

In 1878 Warren Upham published a description of the terraces in the upper part of the valley, in New Hampshire and Vermont, in the third

volume of the *Geology of New Hampshire*. This is a praiseworthy paper, based on detailed study of 200 miles of the valley with spirit-level measurements of the terrace altitudes and without good base maps.

Upham's conception of the large element in the problem was unlike that of either Dana or Hitchcock. He allowed no depression of the land, but, following Adhémar, thought that the gravitational attraction of the ice body on the sea deepened the ocean in the northern region.

"It seems quite probable that the submergence of the Glacial period, of which we have proof, amounting to 50 feet in southern New England, 200 feet on the coast of Maine, and about 400 feet in the valley of the Saint Lawrence, was not caused by any downward and upward movement of the earth's surface, but by the attraction of the immense masses of ice." . . .

Upham's claim that "neither the deposition nor terracing of the modified drift requires any submergence, as by lakes or sea" (page 175), apparently was meant to apply only to the New Hampshire section of the valley; for, accepting statements made by E. Howe, Jr. (*Popular Science Monthly*, volume 10, page 440), he writes:

"These glacial sheets, when at their greatest extent and depth, caused the sea to rise 200 feet higher than now at Long Island, as shown by marine shells" (page 331).

"The valley of the Hudson River was also filled with modified drift to a height at Albany of 330 feet above the sea" (page 332).

This would seem to concede that the terraces in the Massachusetts and Connecticut section of the valley might have been built in sealevel waters. And granting a stand of the sea at 330 feet at Albany should naturally require a similar height of sea on the south border of New Hampshire, in the same latitude and only 60 miles east. His "normal" terraces on this latitude are beneath this height of 330 feet.

The recognition of static-water influence in the lower section of the valley might have suggested similar effects farther north. Upham's description of the valley features begins at the river head, in Connecticut Lake, and proceeds down-stream. If his field-work had the same sequence it helps to explain the non-recognition of the static water features in the lower sections of the valley. From its source to the mouth of the Passumpsic River, about 83 miles, the Connecticut River was above the marine plane and the detrital deposits are to be credited wholly to the river. Below that point the valley features are very different, as he recognized. (See below, page 225.)

Holding the theory of the flooded river as the only effective agent, the author probably realized the inconsistency of the weak features in the

upper, narrow valley, while recognizing in the lower valley a river of such enormous volume as to account for the high "tributary deltas." Certainly he left the deltas hung up in the air and without sufficient explanation.

While Upham could not admit any depression of the land in glacial time, yet he thought that after the departure of the ice-sheet the sea stood below its present level, which implies a rise of the land; and he appeals to this to explain the disappearance of the enormous volume of detritus that under the river theory must have been swept into the sea at the river mouth.

Conceding that the invasion of ocean waters in the Hudson and Saint Lawrence valleys was due to the attraction of the glacier, then as the ice-body waned and the gravitational force decreased, the water surface should have fallen. Consequently the marine plane should decline toward the north, instead of rising.

WORK OF B. K. EMERSON

In the State of Massachusetts the Pleistocene features of the Connecticut Valley were carefully studied for many years by Professor Emerson, and his results are found in two admirable publications by the U. S. Geological Survey, "Geology of Old Hampshire County, Massachusetts," Monograph XXIX, 1898, and the Holyoke Folio, Number 50, 1898.

Professor Emerson recognized that the terraces and all the plains except the very lowest in the valley were the product of static waters, and that the highest deltas or sand plains on the borders of the open valley indicated the summit level of those waters. He credited to the river only the lowest terraces, as floodplains. The level of the standing water in the open valley he accurately differentiated from the higher and varied levels of the deposits made by streams and by glacial lakes. He was non-committal as to the nature or control of the static waters and simply called them the "Connecticut lakes." He did not attempt to show their extent north and south of his State, nor to determine the barrier or outlet.

The name "lakes" as used by Emerson is not inappropriate, in his description of the local features, even if it be understood that the waters were an extension of or confluent with the sea, since the connection with the sea was by two narrow straits, the gorge of the Connecticut below Middletown and the Quinnipiac Valley at New Haven, and the water was kept fresh by the southward current.

Professor Emerson did not publish any diagrams or profiles of the ter-

aces or the water-plane, but he clearly states that the water-plane lies today at 400 feet above tide on the north boundary of the State and at 288 feet on the south boundary. These figures are adopted for the datum plane of the Connecticut Valley sealevel waters and are found to coincide very closely with the highest shoreline features. (See the diagram, plate 10.)

THE RIVER THEORY; DIFFICULTIES AND INCONSISTENCIES

THE UPPER AND THE LOWER VALLEY

The mouth of the Passumpsic River, at the foot of the "Fifteen-miles Falls," is made by Upham the division between the "upper" and the "lower" valley. He found very conspicuous differences between the two sections of the great valley, and these differences are suggestive and important in the light of present knowledge. Speaking of the 20 miles of upper valley, with steep gradient, immediately above the division point, he says:

"The noticeable features of the valley in this distance are that it is deep and narrow, with sloping sides of till, and destitute of the level alluvial terraces and intervals which occupy a large width everywhere else along the river" (page 24).

In contrast, he writes of the lower valley:

"The modified drift of this lower valley is everywhere well developed and occurs in extensive terraces of various heights, three or four often on each side, the upper one being usually from 150 to 200 feet above the river" . . . (page 26).

No explanation is offered for the change in the character and amount of deposits at this point in the valley. If the terraces were all river work, then the valley clear to its head should have been filled with detritus, the same as the lower valley, since the source of material was chiefly from the melting ice and filled the valley from south to north, following the receding ice-front.

The true explanation of the difference between the two sections of the valley is found in the fact that the lower section of the valley was occupied by the sealevel static waters, while the upper section was above the marine plane and held only the river. The lower valley contains all the detritus that was swept out of the upper valley by the river flow. By reference to the diagram it will be seen that the hypothetic or datum plane (plate 10) lies at 650 feet at the mouth of the Passumpsic River,

latitude about $44^{\circ} 17'$, which is precisely the figure that Upham gives for his "normal" terrace at that point.

DELTA'S

The most conspicuous features in the northern part of the "lower" valley (the section forming the boundary between Vermont and New Hampshire and south of the mouth of the Passumpsic River) are the high sand plains, the deltas of tributary streams. In some stretches it is possible that the valley was filled clear across except for the current channel. In such cases the water would have been a true river, but practically at the level of the standing waters below.

Upham says of the deltas:

"Tributary streams . . . frequently formed extensive deposits, . . . similar in material to the floodplain in the main valley, but having a greater height. Sometimes these deltas, being partially undermined, form conspicuous terraces a hundred feet above the highest normal terrace, which is the remnant of the river's continuous floodplain" (page 16).

Several of the heavier deltas are well described by Upham: of Wells and Ammonoosuc rivers, at Wells River and Woodsville (page 29); at mouth of Jacobs Brook, in Fairlee and Oxford (pages 33, 34); Mink Brook, at Hanover (page 38); Lulls Brook, at Hartland (page 41); Little Sugar, Black and Williams rivers (page 51); Black River (page 52); Cold and Saxtons rivers, below Bellows Falls (page 54); at Northfield, Massachusetts (page 57).

Upham's explanation of the great discrepancy between the height of the "normal" terrace and the "tributary" delta terrace is that "the accumulation was too great to be cleared away by the current in the main valley" (page 33). Dana criticised this hanging up of the side deltas so far above the main stream, and he took the summit of the deltas as marking the flood level; but his gain in consistency in the genesis of the deltas was overbalanced by the inconsistencies and difficulties involved in assuming such an immense flood (*American Journal of Science*, volume 23, page 96).

The form of some of the tributary deltas is evidence that they were not built into a river having the strong flow that the assumed gradient would demand. Built in a vigorous river, the deltas would be chiefly developed on the down-stream side, in this case on the south side of the mouth of the tributary. This is not apparent. But it is true that the most effective winds were from the north, and the currents due to winds and water supply toward the south. Moreover, with the lifting of the land and

relative lowering of the waters, with the reduction in the dimensions of the valley, the southward current became more effective. Consequently the inferior terraces, specially in narrow sections of the valley, undoubtedly exhibit some effects of the southward currents. It will be difficult to distinguish the lower terraces from the true river plains. It is possible that in narrow stretches of the New Hampshire section some of the delta terraces will show effects of current in the open valley.

The form and structure of some deltas prove that they were never eroded by any current past their front, though they are bisected and eroded by the stream that built them. The convex front of these deltas, with their constructional frontal slope intact, as shown by the forest beds, prove their construction in quiet water. Mink Brook delta, at Hanover, New Hampshire, shows clearly its constructional frontal slope and lack of undercutting.

In the wider valley, in Massachusetts and Connecticut, many of the broad detrital plains lie in secluded areas or so sheltered that river work is positively ruled out.

TERRACES

Occurrence.—The benching or terracing of the detrital deposits in the Connecticut Valley, and specially in the narrower New Hampshire section, is the feature which has been chiefly discussed by the former writers and which has been taken as the main evidence of river work.

The higher terraces are developed on the deltas, the detrital deposits at the mouths of the side valleys, and they are very weak or entirely lacking in the longer intervals between the deltas. This fact discredits the river theory, for a river of great volume and steep gradient, such as must be assumed here, would sweep the detritus down its course and build it as floodplains in the embayments or slack-water areas.

Discordance.—The want of uniformity in the altitude of the higher of the "normal" terraces and the lack of continuity throws another doubt on their origin as river plains. An example of this discordance may be quoted from Upham:

"In Thetford and Lyme we come to an abrupt change in the height of the upper terrace plain. . . . At North Thetford this line of the highest terrace suddenly rises to 525 (from 440) and in a mile and a half farther south to 524 feet" (page 35).

This variation in altitude in short distances, with discontinuity, is a character that does not belong to river plains. Rivers flowing freely make floodplains uniform in gradient and consequent altitude, even if somewhat discontinuous.

Terraces in the Hudson-Champlain Valley.—Terraces are displayed in the Hudson and Champlain Valley on even a larger scale than in the Connecticut Valley. They are more conspicuous in the latter valley and for longer distances because of the narrowness of the valley and the smaller size and closer grouping of the benchings. In the Hudson-Champlain the terraces usually do not lie grouped within the range of close vision.

A remarkable benching of detrital deposits is exhibited in the Hudson Valley from Troy north to Glens Falls. Into this stretch of 45 miles of sealevel water five rivers poured their glacial flood—the Mohawk, Hoosick, Anthony Kill, Fish Creek, Batten Kill, and the upper Hudson. An enormous volume of detritus was swept into the slowly falling waters of the marine inlet. Wave and current action combined, working at successively lower levels on the deposits, produced a display of terraces on a large scale. For illustration the reader may look at the Cohoes, New York, topographic sheet. The terraces of the Hoosick delta shown on this sheet have been discussed and figured by Professor Woodworth in New York State Museum Bulletin No. 84, pages 134, 200, and plate 24.

Perhaps the finest example of terraces, and comparable in every way to the Connecticut Valley features, is found on the delta of the Winooski at Burlington, Vermont, and up the Winooski Valley as far as Montpelier. On the Burlington sheet the terraces are shown at all levels from Lake Champlain (100 feet) up to 500 feet. The reader might claim that these are river-made terraces, since they lie in the river valley and on its delta. This is not true. There was another agent involved. We know that oceanic waters occupied the Champlain and Winooski valleys when these elevated deposits were made. The writer finds clear evidence of the standing waters up to height of at least 640 feet on the parallel of Burlington. The Winooski delta was built in the open waters of the great Champlain Valley, and the splendid display of terraces was carved in the subsiding static waters by the combined work of waves and currents. The sealevel waters extended southeast up the narrow Winooski Valley to beyond Montpelier, and the terracing of deposits on the valley walls are abundant and conspicuous, like those in the upper Connecticut Valley. We have in the Winooski features a record of the same history as in the Connecticut Valley: a narrow valley, deeply flooded with sea-level waters, abundant inwash of detritus by tributary streams, and the benching of the deposits by wave erosion and gentle currents, due to the slow outflow of the lowering waters. The action was not that of a river, but of an "inlet."

Other examples of terracing are found: at Port Kent, on the delta of the Ausable; in the Hudson Valley, at Catskill, Kingston, Newburg, and Haverstraw. The fact that the benchings are not conspicuous or visible in groups from single viewpoints has no bearing on the question of their genesis.

Origin.—Enough has been said to make the fact clear that the terraces of the Connecticut Valley, like those in the Winooski, Champlain, and Hudson, are not the product of simple river work, but were made by the combined action of subsiding static waters, inflowing tributaries and outflowing currents. The important fact to recognize is that the terraces were formed in static waters. Whether these waters were lake or sea is another matter.

At the higher levels the wave-work of the static water and the tributary stream inflow were the more effective factors. With the falling of the water level and consequent restriction of the area the outflowing currents increased in effectiveness, until finally the river was left as the sole agent, producing the plains at, and possibly just above, the present river level.

DETRITUS.

Character.—The fine composition or clayey character of most of the material composing the terraces and the difficulty of explaining it under the river theory was recognized by Dana. Illustrating this we quote:

“From the above, the mean velocity for the whole river from Haverhill to Middletown would have been, assuming that the relations of the land to the sealevel were the same as now, over 12 miles an hour, even supposing the mean width to have been but 2,500 feet.

“This great velocity, or even one of 10 miles an hour, is not compatible with the character of the deposits which lie at different levels beneath the surface of the stream, both those at 140 feet below the surface and those at higher levels” (American Journal of Science, vol. 23, page 192).

“It is to be remembered that the sand beds and those of finer material ordinarily make not only the lower terraces, but also the highest, where tributaries are absent to within 50 or often 20 or 30 feet of their tops, and that this is so even high up the Connecticut, as at Barnet, not two miles south of the junction with the Passumpsic, where these finer deposits extended to a level of 150 to 200 feet above low water in the river” (page 194).

To reduce the velocity of the supposed river, appeal was first made to dams; but such were ruled out, except a possible ice-jam below Middletown. Dana says:

“For making the clay-beds north of Amherst the Middletown dam would have been of no avail, and besides this dam there is no satisfactory evidence of any other” (page 195).

Appeal was then made to the depressed attitude of the land during the ice waning, as shown by marine fossils. Taking the uplift at New Haven as 15 to 25 feet; Middlebury, Vermont, at 403, and Montreal, 520 (page 196), he calculated a mean rate of uplift northward along the Connecticut Valley at 1.25 feet per mile (page 198). From this Dana calculates the water surface at the Middletown dam (?) as 137 feet; Springfield, 135; South Vernon, 236; Windsor, 299, and Haverhill, 383 feet (page 199). This calculation reduced the gradient of the imaginary river, but yet failed to harmonize the facts. After further discussion and calculation, he says:

"But it is not so evident what slope would harmonize the facts; that is, would cause a velocity sufficient to make or leave coarse valley deposits near and at flood level, . . . and at the same time leave almost undisturbed beds of sand or of fine pebbles along its bottom" . . . (page 200).

The article ends with the difficulty unsettled. But the difficulties all disappear under the recognition of a Connecticut marine inlet instead of a river.

Amount.—The river theory involves difficulty when the volume of detritus is considered. Both Dana and Upham thought that the valley had been filled with alluvial material up to the level of the higher terraces, and that the filling had been swept out by the river in its diminished flow after the glacial flood.

"In this way the Connecticut River . . . has excavated its ancient high floodplain of the Champlain period to a depth of from 150 to 200 feet" . . . (Upham, page 15).

"The formation of the terraces has taken place by excavation of a vast deposit that filled the river valley with these upper plains" . . . (page 59).

Upham gives the widths in the New Hampshire section of the valley up to $2\frac{1}{2}$ miles and an average of fully 1 mile. If we take the greater width at the summit of the deltas, it is over 4 miles.

In Massachusetts and Connecticut the width of the valley between the high terraces is from a few miles up to 12 or more. Detrital plains occur in the very wide as well as in the narrow sections. If the volume of the river, without dams, was great enough to occupy the wide sections of the valley at Hartford and Springfield, it would have left no detritus in the constricted sections.

One condition seems not to have been recognized. The deposition of detritus was not a process of down-stream migration or the eroding of an upper section of the valley to supply material to fill a lower section. The valley was opened by the recession of the ice-front from south to north,

and the glacial flood existed all that time, following the glacier. Therefore the fill of the valley with the stream detritus proceeded from south to north, and the volume of detritus would have been as great as if the valley had been wholly filled its entire length at one moment. Considered in its implications, this is an unreasonable amount.

Disposition.—The fate of such an enormous volume of alluvial material as the river theory requires is a serious difficulty. Where is the detritus now? It had to be dropped when the river reached sealevel. To Dana this was in Connecticut, in which case the broad valley should have been filled below Hartford with a great delta plain. There are no remnants of such plain. Even if such plain has been carried away, it should reappear farther south as a delta in Long Island Sound.

The only recognition of this problem was by Upham, who suggested that after the ice-cap disappeared the ocean might have stood beneath its present level. But the Coast Survey charts do not indicate any submerged deltas.

The truth is that the valley never contained much more detritus than it does today. The deposits from the tributary streams were laid along the margins of the sealevel waters, but those from the glacial outwash were swept into the open valley. During the subsidence of the waters (land uplifting) some of the detritus was rinsed down the slopes and reaccumulated at lower levels. The lower terraces are therefore of finer material, more massive, more continuous, and with greater resemblance to river plains, into which they blend at or near the valley bottom. When the river came into life, which it did very gradually, such detritus as it could grasp in its eroding stretches was dropped farther down in the slack-water areas, forming the lower plains which we see today in the southern part of the valley.

Lower series of plains.—Upham refers to a set of lower terraces, more continuous or connected in series than the upper, "normal" terraces. He suggested that they might indicate a pause in the river erosion. Such hesitation in the relative lowering of the waters would really be due to a relative pause in the rising of the land. It is possible that the rate of uplift was not uniform.

However, it may be that the series of more continuous plains only represent the dominance of outflowing currents or initial stream-work, at the lower levels, over the static water effects which dominated at the higher levels.

The lower, broader plains have an altitude in the New Haven-Hartford region of about 100 feet, at Springfield about 200 feet, and at Brattleboro about 300 feet. They lie something like 100 feet beneath the summit

plane of the marine waters. Without study directed to this point we can not know if this correspondence has any significance, as suggesting a relative pause in the uplifting of the land, or whether the broader development of the lower plains is merely due to the topography of the valley.

MEANDERS; OX-BOWS

If the terraces were the product of river work they should exhibit the characteristic features due to streams, such as meanders, channels, ox-bows or cut-offs, etcetera. The edges of the terraces should be frequently scalloped, or cut into concavities and cusps. The writer is not aware of any clear features of these kinds at the higher levels. They should occur near the level of the present river and on its graded floodplain. Emerson's map in folio 50 shows such river features in his "Terraces of Erosion," which lie at low levels and evidently are the work of the Connecticut River; but his "Terraces of Construction," at the higher levels and above the range of the present river, do not exhibit the features characteristic of river work.

KETTLES

The occurrence of glacial kettles in the Connecticut Valley has been thought to argue against deep and long submergence of the area. Kettles large enough to be represented on the topographic maps are few. The largest appear on the Middletown sheet, lying east of Portland, at altitude about 100 feet. Small kettles are shown on the New Haven and the Hartford sheets, at various altitudes up to 200 feet. The writer has seen none of the kettles and can discuss them only in a theoretic way.

The objections to long submergence of the kettles or their localities would apply with more force to the river theory. The burial of the ice-blocks took place at the margin of the ice-sheet. If the ice melted out and the detrital cover slumped in while the mass was submerged in the river, the drifting detritus would be more likely to fill and so destroy the basin; but in the more quiet standing water the basins would have much better chance of escaping unfilled. It would also seem that detached ice-blocks would be buried much more easily when the ice was faced by standing water than when the glacial outwash formed rivers.

When kettles lie in definite terraces or other deposits that were built or shaped by either stream or waves, it follows that the slumping occurred subsequent to the completion of the deposit, and this may imply a long time of burial of the ice before its melting. The physical factors here involved require consideration. We assume marine submergence.

When the ice-block was detached from the front of the glacier the temperature of the waters and the detritus was near 32 degrees Fahrenheit. The mass of buried ice and its detrital cover were practically at freezing temperature. For a long time, while the ice-front was in the neighborhood, the accumulating deposits were very cold. During all the time, certainly thousands of years, that the ice-sheet lay across the Connecticut Valley, the outflow from the glacier was a cold, bottom current or drift southward down the inlet. Then even after the glacial flood ceased the more quiet water at the bottom of the inlet could not readily be warmed above the maximum density, whatever that was, depending on the salinity. Circulation of the water in the cold gravels or sand or clay at the bottom of the standing water was certainly sluggish and ineffective.

All the conditions would seem to favor the preservation of the buried ice-block, and it seems probable that the larger blocks and those buried more deeply did not melt until the locality was lifted out of the water and exposed to the sun and atmosphere. Doubtless some ice-blocks did melt in time for detrital filling of the depressions, in which case we find as kettles only the few basins that were very late in forming.

Such kettles as lie in areas of submergence that were never subjected to stream flow or currents, or even to currents which carried no detritus, might have formed quickly and yet have remained unfilled.

MARINE SUBMERGENCE

THEORETIC PLANE

The Connecticut Valley can not properly be studied alone. Any up and down movement of the land must have involved wide territory. The other valleys of New England and the Hudson-Champlain must be used in comparison.

In the Hudson-Champlain Valley, with its greater dimensions and larger drainage area, the summit-level phenomena are stronger and more definite than in the Connecticut Valley. They afford a clearer history and stronger argument for the reasons that no one could suggest river work and because the great valley extends north at low altitude, so as to connect New York Bay with the Saint Lawrence depression. The phenomena due to marine submergence can be compared with present sea-level at both ends of the valley and the marine plane be determined more accurately. The Connecticut Valley rises rapidly in its head-waters section and the sealevel waters extended north only to the mouth of the Passumpsic River.

The uplifted and tilted plane of the sealevel waters is indicated in the

chart, plate 11, for both the Connecticut and the Hudson-Champlain valleys. The form of this chart is borrowed from Woodworth's Plate 28, in Bulletin 84, New York State Museum. For the Connecticut Valley the theoretic or datum plane is based on Emerson's figures, 288 feet on the south line of Massachusetts and 400 feet on the north boundary. So far as observation has reached, the summit-level phenomena throughout the valley agree remarkably close with this hypothetical plane.

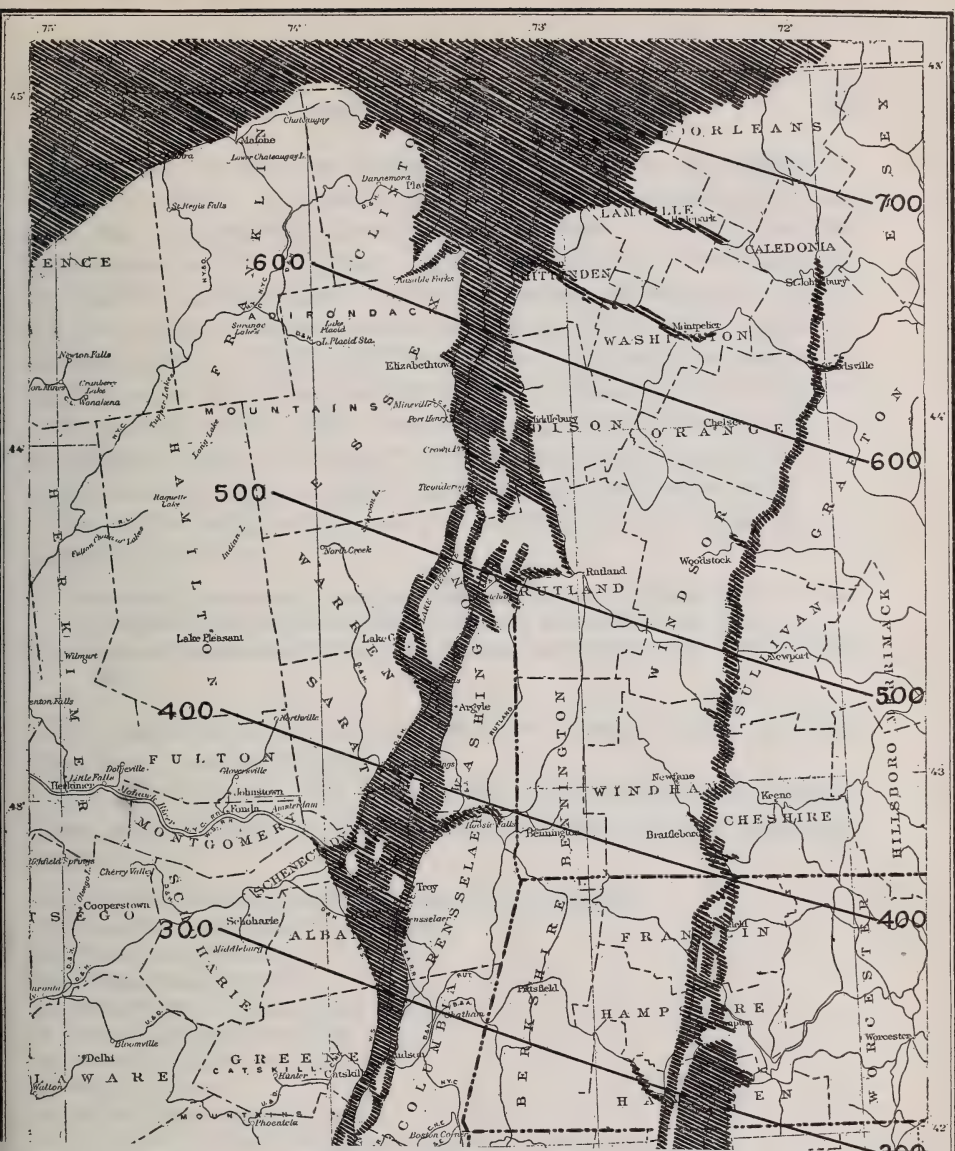
The line representing the Hudson Valley plane is drawn coincident with numerous summit features.

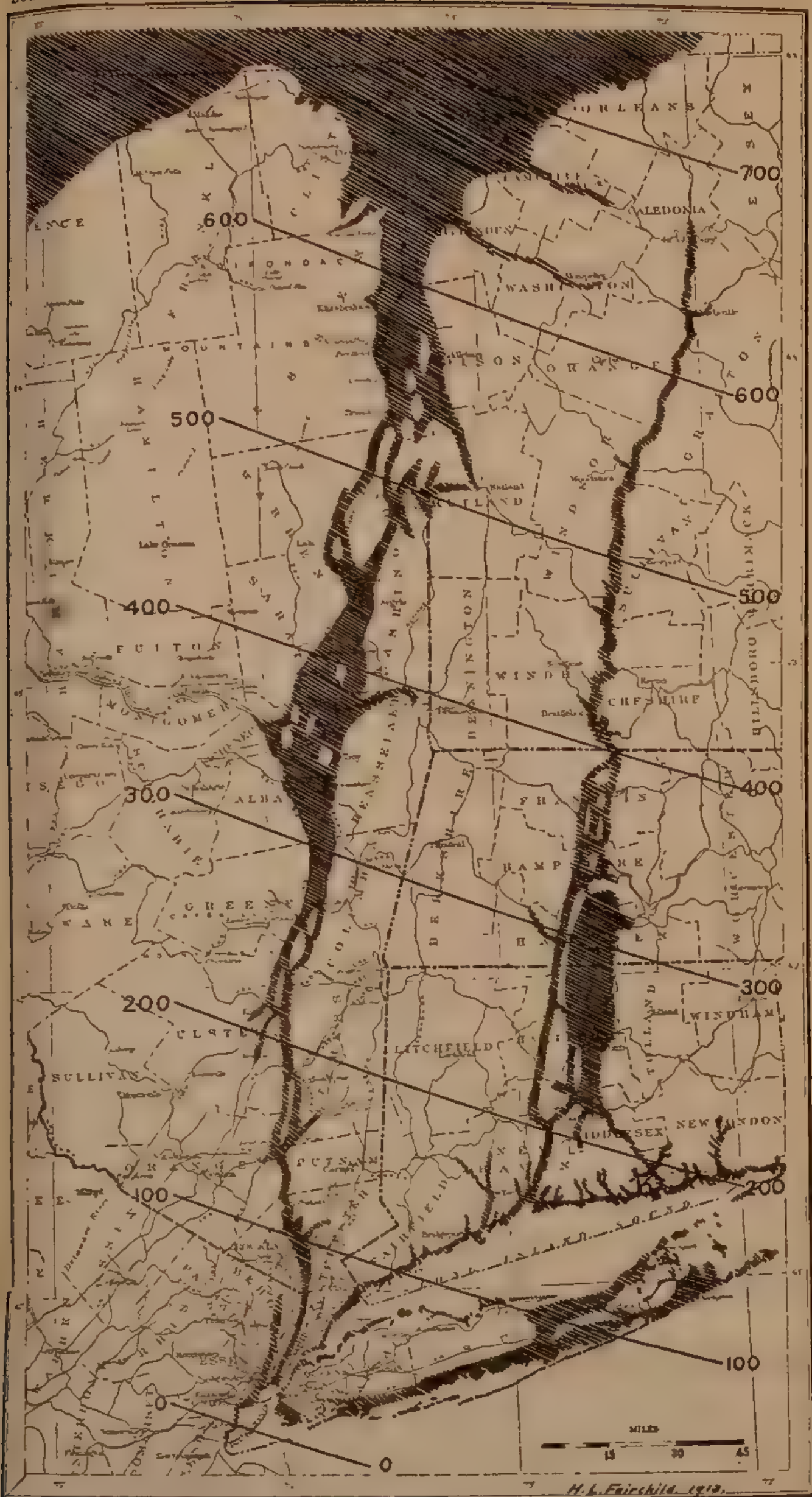
It is not supposed that the actual uplifted and tilted marine plane is a perfectly straight surface, but such irregularities or warping as exists would probably not be evident in the condensed chart. The area of New England and New York probably was not uplifted as a rigid mass, yet any wavelike uplift following the waning ice-body might in its final result approach the regularity of a plane. The altitude variations of the shoreline features of the summit level will usually not vary from the indicated plane more than the natural variation in height of such phenomena combined with the errors of measurement that refer to the 20-foot contours of the old topographic sheets.

Shoreline features or phenomena of standing water found much above this datum plane will belong to glacial waters held up by the ice-front. When evidences of standing water are found much below this plane, search should be carefully made for higher features; but it should be emphasized that local absence of shoreline features is very common, and such negation has no weight against positive occurrence of the phenomena at other places. Long stretches of shoreline may yield very faint evidence or even none at all.

The slope or gradient of the marine plane in the Connecticut Valley is 2.30 feet per mile. In the Hudson Valley it is 2.23 feet per mile. This close correspondence is not closer than should be expected. But in the Connecticut Valley the plane lies about 50 feet higher than in the Hudson. This throws the isobases about 20 degrees north of west by 20 degrees south of east, as depicted in the map, plate 11.

In the northern part of the valleys the marine plane apparently has a steeper gradient, or, in other words, the original plane is warped upward at an increasing rate in the Champlain Valley and probably in the New Hampshire portion of the Connecticut Valley. In the Champlain Valley heavy beaches which can not be referred to glacial lakes lie much above our datum plane, which at the international boundary is about 695 feet, while strong cobble bars occur two miles south at 730 feet.





PLEISTOCENE MARINE SUBMERGENCE OF THE CONNECTICUT AND HUDSON-CHAMPLAIN VALLEYS

The shaded areas were flooded by sealevel waters as the latest ice-sheet deserted the territory. Isobasal lines show present altitudes, in feet, of the theoretic or datum marine plane. The Champlain Valley, and probably the upper part of the Connecticut Valley, have been upwarped higher than the datum plane.

Exact data for the New Hampshire section are not yet available in sufficient amount. At Hanover the datum plane marks about 555 feet, but a fair bar, apparently formed in submergence, is 565 feet, and the delta terraces are 575 or higher. Beyond the north line of Massachusetts the available data is meager. The writer has seen the abundant features, but has not taken measurements on the summit level. The figures for altitudes given by Upham and Dana can not confidently be used, since they did not recognize standing water and in consequence did not discriminate the static plane. The "normal" terraces are far below the level of the standing waters, while the "tributary," or delta, terrace levels evidently include floodplain deposits much above the static water level.

Connecticut valley references.—The numerals refer to the features indicated on the chart.

- 22. Portland, Connecticut. Two heavy gravel bars on west side of hill, in the northwest part of the village, at 200 and 220 feet by the map.
- 27. Plains at Manchester, Connecticut, 9 miles east of Hartford. Summit, 260 feet.

For Massachusetts the reader is referred to Emerson's maps, the datum plane being based on his data.

For New Hampshire and Vermont the data are taken from Upham's paper, except number 64. The altitudes are those given for "tributary" deltas.

- 44. Northfield, Massachusetts, delta terraces, 375-390 feet.
- 46. Hinsdale, New Hampshire, 380-430.
- 48. Brattleboro, 409-425.
- 49. Dummerston, 420-440.
- 53. Bellows Falls, 1 mile south, 465-486.
- 57. North Chesterton, 475-530.
- 59. West Claremont, 520-540.
- 60. Windsor, 540.
- 63. White River Junction, 550.
- 64. Hanover, delta of Mink Brook; bar, 565; upper terraces, 575.
- 65. Mouth of Pampanoosic River, 590.
- 68. Oxford and Fairlee, 560-590.
- 70. Piermont, 500-650.
- 71. Bradford, up to 600.
- 73. Wells River, 600-660.
- 76. Stevens River, 675.
- 77. Mouth of Passumpsic River, 650, "normal."

Farther north the river valley lies above the marine plane.

Hudson-Champlain valley references.—From New York Bay northward to Haverstraw Bay numerous terraces have close agreement with the

datum plane, but they require more precise measurement. These will be inserted in a future report for New York State.

22. Croton Point delta, 100 feet (Woodworth's number 4). Silt plain south of Short Clove, 2 miles south of Haverstraw, 100-120 feet.
24. Haverstraw to Stony Point, 100-120.
27. Fort Montgomery, bar, 140.
29. West Point terraces, 150-160; Cold Spring terraces, 160.
32. Newburg deltas and Beacon deltas, 160.
33. Beacon, broad plain, 140.
36. Marlboro and Wappinger Falls, 160.
39. Poughkeepsie, broad plain, including Vassar campus, 180.
41. Hyde Park terrace plain, 200 (Woodworth's number 10).
42. Rosendale Plains, delta of Wallkill and Rondout rivers, up to 220.
46. Kingston, delta of Esopus Creek; Kingston Point and Port Ewen terraces; broad plains at Rhinebeck, 220.
50. Mount Marion glacial stream channel, 2 miles southwest of Saugerties, 240.
54. Great Falls, 6 miles north of Saugerties, glacial stream channel, 260.
55. Greendale, 3 miles southeast of Catskill, bars, 240; terraces, 260.
61. Kinderhook, plains west of Kinderhook Lake, 300.
65. South Bethlehem, 10 miles southwest of Albany, terraces, 310.
70. Voorheesville, 9 miles west of Albany, glacial channel, 340.
74. Schenectady, Mohawk River delta, 350.
76. High Mills, delta plain 5 miles north of Schenectady, 360.
77. Schaghticoke, Hoosick River delta summit, 375.
78. Mechanicsville, gravel bar 3 miles northwest, 380.
79. Ballston Spa, 3 miles southwest, Mourning Kill delta, 390.
81. Ballston Spa, broad sand plains, delta of Kayaderosseras Creek, 400.
83. Greenwich, Batten Kill delta, 510.
87. Fort Edward, 5 miles southwest and south of Durkeetown, heavy bars, 420.
89. Glens Falls, 5 miles southwest, east of Palmertown Mountain, Hudson River delta, gravel bars, 440. In Argyle, 5 miles east of Fort Edward, wave-cutting in shales, up to 440.
93. Glens Falls, 6 miles north, southeast side of French Mountain, terraces, 440 and upward.
108. Brandon, Vermont, for 3 miles north of village, bars, cliffs, and terraces up to 520. Seven miles northwest, in Whiting and Sudbury, wave-work and bars from 520 down to 400.
109. Ticonderoga, 3 miles northwest, at Street Road, gravel bars on kame area from 360 to at least 500 (Woodworth's number 31).
111. Crown Point, bars 3 miles northwest, about 530 (Woodworth's number 32). Terraces west of Crown Point beautifully displayed up to 500.
113. Middlebury, Vermont, bars around Chipman Hill, north of the village, up to 540.
114. Port Henry, bars $1\frac{1}{2}$ miles southwest, 530-630. Terraces west and northwest of village, up to 640.
123. Essex, 4 miles west of village and northwest of East Bouquet Mountain, terraces up to 610.

124. Essex, $1\frac{1}{2}$ miles northwest of East Bouquet Mountain, bars from 500 to 550.
127. Burlington, Vermont, 7 miles east and $1\frac{1}{2}$ miles northwest of Williston, gravel bar, 610.
128. Burlington, 10 miles east, on northeast corner of Burlington quadrangle, east side of Saxon Hill, cliff and plain, 646.
129. Port Kent, 2 miles southwest, heavy gravel bars on northwest slope of Trembleau Mountain, 450-585 (Woodworth's number 43); 8 miles west, at Harkness, bars both sides of Ausable Valley at 500-580; 4 miles southwest and 1 mile southeast of Keeseville, bars on north slope of Prospect Hill at 585.
131. Peru, 3 miles west, glacial channels at 700; bars at 706 down to 500.
132. Schuyler Falls, 2 miles northwest and 7 miles southwest of Plattsburg, heavy gravel bars, 540-630; cliff at 630.
133. Morrisonville, 3 miles southwest, glacial channels down to or below 700.
134. Morrisonville, 2 miles southwest, bars, 635 down to 560.
136. West Beekmantown, $1\frac{1}{2}$ miles south by west and 7 miles northwest of Plattsburg, on north edge of Dannemora quadrangle, heavy bars, 645 down to 560.
138. West Chazy, 3 miles southwest, bars, 680 down to 600.
139. West Chazy, 3 miles northwest, Cobblestone Hill, heavy bars, 660 down to 580 (Woodworth's number 50).
140. Altona, bars about 700; terraces, 720.
143. Cannon Corners, 8 miles west of Mooers, heavy bars extending for 3 miles north and south, 695 to 735; glacial channels, down to 720; heavy cobble deltas, 750 down to 700. (Woodworth's number 53 refers to bars $2\frac{1}{2}$ miles north of Cannon Corners, in the extreme corner of Mooers quadrangle, at 730 to 710.)
145. Covey Hill Post-office, one-half mile west, on slope of hill, cliffs and terraces, inconspicuous, 640 and 725.

The series of heavy bars north and south of the international boundary, well known as the Covey Hill beaches, are indicated on the diagram but not numbered. They range from 525 feet down to 300 and lower, and represent an inferior stage of the sealevel waters. From Covey Hill Post-office they extend westward about the slope, reentering New York north of Chateaugay, and have been mapped through the Saint Lawrence into the Ontario Valley. They are the beaches of the "Gilbert Gulf."

The features given in the chart are only part of those which mark the highest level of the valley-wide standing water. The inferior phenomena are profuse and commonly obtrusive, and while of value as showing effective water action they are not important in the present study. More data could be added for the summit plane, but these are thought sufficient to fairly show the present attitude and gradient of the uplifted marine planes.

The student of this subject will be able to use the chart for the discovery and mapping of shore features, and the numbering is left open to permit insertion of new data.

In territory east or west of either valley some recognition should be given to the variation of the isobases from the latitude parallels. It is estimated that the variation in altitude going east or west is about 0.8 feet per mile; this is to be deducted toward the west and added eastward. In illustration of this variation two localities may be noted. Prof. Joseph Barrell showed the writer a small but excellent delta at Westville, a northwestern suburb of New Haven, the summit altitude of which according to the map is 165 to 170 feet. This is about 15 feet low for the same latitude on the Connecticut River, but, being 18 miles west, is near the theoretic height. Prof. H. E. Gregory pointed out the elegant sand plains in the Naugatuck Valley at Seymour, Connecticut. The map altitude is 160 to 180 feet. If we take 170 feet as the best figure, we find it is about 20 feet under the datum plane for the latitude ($41^{\circ} 23'$). Seymour lies 22 miles west of Middletown, which makes the water level 17.6 feet lower. Of course these figures are not precise, but merely illustrate the principle.

COMPARISON OF DATA

Taking the continental depression at Montreal as 520 feet Dana calculated the rate of uplift as 1.5 to 1.25 feet per mile (volume 23, pages 197-198). On this basis he estimated the marine plane at several localities in the Connecticut Valley. The following table gives Dana's figures for his marine plane and his river flood levels in comparison with what is now regarded as the approximately true marine plane:

Locality.	Dana's marine plane.	Dana's flood level.	Theoretic plane.	Upham's figures.
Montreal	520	.....	830	.....
Stratford Hollow....	345	960	710	} Valley above the ma- rine level.
Lancaster	318	910	675	
Low. Waterford.....	.....	843	650	} 618, "normal."
Barnet	295	677	640	
Wells River.....	.....	660	620	} 600-660, "tributary."
Haverhill	272	655	605	
Hanover .....	.....	580	555	.....
Hartland .....	.....	550	530	540, normal.
Windsor .....	.....	520	520	.....
Bellows Falls.....	.....	480	465	540, tributary.
Brattleboro .....	.....	410	425	465-480, tributary.
South Vernon.....	160	396	405	409-425, tributary.
North line of Mass. ....	.....	.....	400	.....
Northfield .....	.....	390	395	.....
North Hatfield.....	.....	312	350	375-390, tributary.
Springfield .....	.....	240	300	.....
South line of Mass. ....	.....	230	288	.....
Hartford .....	.....	210	250	.....
Middletown.....	.....	195	215	.....
Long Island Sound..	25	25	160-125	.....
Riverhead, L. I. ....	.....	.....	115	.....
Southampton plains.	.....	.....	100	.....

PHENOMENA OF THE SUMMIT LEVEL

The features marking the highest stand of the waters are the ordinary shoreline phenomena, beaches, and deltas. The beach phenomena, as bars and cliffs, are usually not conspicuous, because in the sections of the valley having sufficient width for effective wave-work the marginal waters were either too shallow or too secluded. However, close examination of the valley sides along the theoretic plane will probably discover definite shore features at many localities. Two heavy gravel bars lie northeast of Middletown, on the west side of the hill at Portland, which were found by using the theoretic level. By the map contours the higher bar is 220 feet, which is the precise theoretic altitude of the marine plane.

It needs to be emphasized that absence of expected shore phenomena at any locality, or even along a stretch of shoreline, is not conclusive negative evidence. Shore features are capricious and are often lacking where most confidently expected and where the fact of water is demonstrable by good features on both sides of the negative locality. On the other hand, strong features are frequently discovered where not expected.

Bars and deltas may occur at all altitudes inferior to the summit or initial water level, and more abundantly; hence it is not safe to take the highest feature in isolated localities as marking the summit. Only by

correlation along considerable distances of shoreline can the true summit plane be confidently predicated.

In this glaciated area there is, fortunately, another class of phenomena which is positive as marking the static water summit, even in single occurrence, namely, the channels and deltas of glacial drainage. The ice-border drainage was ephemeral and it dropped its detritus in the waters that were laving the ice-front and which were then at their maximum altitude. Glacial stream channels and the sand and gravel plains which can be correlated with the debouchure of glacial streams give the approximate marine plane. The writer has not sought these features on the sides of the Connecticut Valley, but they must certainly occur there abundantly. In the Hudson-Champlain Valley they have afforded positive data.

Naturally the summit-plane phenomena in the broader sections of the valley are relatively weak and inconspicuous, and it is not surprising that in the lower stretch of the Connecticut Valley they have been overlooked. They must be sought with some idea of the proper altitude.

There are several reasons for the weakness of the summit features. The sealevel waters soon fell away from their summit plane, due to the rising of the land. Of the rate of land uplift we have no idea, but it was doubtless in progress as the ice-sheet was waning. The amount of detritus in the grasp of the earliest water was little more than that contributed by streams and glacial outwash. Time was not allowed for the cutting of cliffs and building of bars, except in the most favorable localities. At lower stands of the water detritus was accumulated by the rinsing down of the upper slopes.

In the lower part of the Connecticut Valley, with great width and irregular topography of the walls, the shore phenomena are detached and usually weak and inconspicuous. Naturally they would not be associated in origin or correlated in their altitudes without study directed to that end. A wrong philosophy has prevented the recognition of these scattered features as the products of one high-level water body.

In the New Hampshire section of the valley the deltas of streams, either land or glacial drainage, are the common features which mark the summit water-level. In the Massachusetts-Connecticut section the stream-built sand plains are not evident, as the smaller ones with good form lie far back on the slopes, while the heavier deposits of the larger streams have been spread out as indefinite plains or left as alluvial flats in the lateral or tributary valleys.

It should be understood that the marine waters flooded all the valleys of New England to a height correlating with the plane in the Connecticut Valley, and similar evidence of the standing water will be found in them.

Many of the streams now tributary to the Connecticut River were, during the postglacial submergence, independent streams, and their detrital contributions to the sealevel deposits must be sought at the theoretic elevation and often outside the Connecticut Valley proper. * An inspection of Emerson's maps of the Pleistocene, in his two writings above noted, will show the "high delta sands" and "lake-shore beds" miles back from the river and in lateral valleys now having no essential relation to the present Connecticut River.

GLACIAL DELTAS

The most easily recognized proofs of the high-level waters, and probably the most frequent, are the small deltas of unmistakable form and structure left hung up on the valley sides. These have been attributed to glacial waters, local ice-border lakes or pondings in side valleys or re-entrants of the valley wall. Such genesis of some deltas is certainly possible and the theory is legitimate. In some cases the composition or partial content of the delta argues for the immediate presence of the glacier. But ice-border lakes on the sides of the open valley must have been rare and the production of definite deltas very doubtful, for the following reasons: The writers seem to agree that the waning ice in the Connecticut Valley was not strongly lobate, and a lobate or tongue form is the more favorable for such pondings. Moreover, such waters with outlet alongside the ice border are fluctuating in level and ephemeral. To have steady level, a glacial lake required an outlet over land, and such outlet channel should be found in order to confidently postulate a lateral glacial lake. In lateral valleys with northward down-slope glacial lakes occurred, and Emerson shows such in his maps. Any deltas or other shore phenomena at high level on the sides of the open valley or in south-leading valleys should be attributed to the marine level, and confidently so if the altitude is found to coincide with the theoretic marine plane.

Some deltas deposited in the sealevel waters may have been built near or even against the ice-front, and such might contain unassorted materials. Doubtless some deposits were made by glacial drainage that poured directly from the ice-front or along the ice border, but such deposits are not likely to have good delta form for the reason that such drainage was shifting and commonly subglacial.

FEATURES OF THE LOWER LEVELS

As the land slowly lifted out of the sealevel waters the finer detritus was partially rinsed down the steeper slopes, and with the diminishing breadth and depth of the waters the detrital deposits became broader and more continuous. The conspicuous, extended and clayey plains are inferior levels. As examples we may note: at Broad Brook, 13 miles north-

east of Hartford, 100 to 200 feet (theoretic plane, 275); in Long Meadow, south of Springfield, 200 feet (theoretic, 300); Turner Falls and Greenfield, 300 feet (theoretic, 375); Hanover, 500-540 (theoretic, 565). Passing north, the broad plains more nearly approach the marine level.

If the highest of the broad "flats" in the open valley could reasonably be regarded as indicating the primitive level of the river flood, they certainly can not be so considered for static waters.

In the lowering waters the conditions for production of cliffs and bars became more and more unfavorable. The deltas, being proportionately of finer material, were spread out thinner into indefinite shape and not so clearly correlated with the contributing tributary streams. When the waters became quite contracted the southward currents were still more effective and the detritus still better distributed. Eventually the southward currents of the narrow sections became continuous throughout the valley and constituted the primitive postglacial Connecticut River.

ABSENCE OF MARINE FOSSILS

The two chief objections to the theory (or fact) of marine submergence will be: first, the lack of conspicuous summit-level phenomena, and, second, the absence of marine organisms. The weakness of the shore phenomena at the higher levels has already been sufficiently discussed.

The lack of marine fossils in the Connecticut Valley terraces is not proof of non-marine origin, for the negative evidence is inconclusive. No fresh-water fossils are found, which fact might be used as argument against the river theory. We know that large terranes of oceanic origin are quite destitute of organisms. But there is a positive and satisfactory explanation of the absence of fossils in these sediments.

Even at the summit level the sealevel waters in the valley had connection with the open sea only through the straits at Middletown and New Haven. The lower waters had only one pass to the sea, through the Middletown narrows. Moreover, the valley waters were always freshened by the drainage from the north, and at the higher levels received the copious flood of cold water from the melting ice-sheet. The waters were estuarine, and probably only the southern waters were even brackish. The term "lakes," applied by Emerson, is not inappropriate.

Marine fossils have been reported, but not always verified, from elevated points on Long Island and from various localities in New England. They should be sought in the valleys of Connecticut which open freely southward, but probably they will not be found in the valley of the Connecticut River.

MAGMATIC DIFFERENTIATION AND ASSIMILATION IN
THE ADIRONDACK REGION¹

BY WILLIAM J. MILLER

(Read before the Society December 30, 1913)

CONTENTS

	Page
Introduction.....	243
Facies of the great syenite-granite intrusive body.....	244
General observations.....	244
Normal syenite.....	245
Basic phases of the syenite.....	245
Granitic syenite.....	246
Granite and granite porphyry.....	246
Differentiation of the syenite-granite magma.....	246
Actual examples.....	246
Observations of C. H. Smyth, Jr.....	246
Observations of H. P. Cushing.....	247
Observations of I. H. Ogilvie.....	248
Observations of J. F. Kemp.....	248
Observations of the writer.....	248
General considerations.....	249
Assimilation by the syenite-granite magma.....	254
Actual examples.....	254
Observations of C. H. Smyth, Jr.....	254
Observations of H. P. Cushing.....	255
Observations of the writer.....	255
General considerations.....	260
Original banded structures in the syenite and granite.....	263

INTRODUCTION

The deep-seated conditions to which the present surface rocks of the pre-Cambrian area in northern New York were subjected when the tremendous molten masses were intruded into the thick Grenville sediments were decidedly favorable for both magmatic differentiation and assimila-

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tion. Probably few regions present any better opportunities for the study of such phenomena. It is the purpose of this paper to bring together published and unpublished observations bearing on these problems and to present certain conclusions which have an important bearing not only on Adirondack geology, but also on the broader problems of petrology.

Particular acknowledgments are due Professors Cushing, Kemp, and Smyth, all of whose publications pertaining to the geology of the region are so familiar to the writer. During the past eight years the writer's work has been largely confined to the southern half of the Adirondack region and has resulted in the detailed mapping of about 1,200 square miles of pre-Cambrian rock. Problems of differentiation and assimilation have always been prime considerations.

It is quite generally agreed that the science of petrology is still in its formulative stage. Certainly this stage will never be passed unless generalizations are based on a broad array of detailed observations and facts. Various papers have recently appeared in which speculations and hypotheses occupy prominent places. Such papers are, of course, important, but the basis of fact is often meager. Hence, in the present paper, which deals with an unusually favorable region, much space is given to detailed descriptions illustrating various phases of differentiation and assimilation.

This paper deals directly only with the great bodies of syenite and granite and their influence on the Grenville rocks into which they have been intruded in the Adirondack region. The large body of anorthosite, which lies mostly in Essex County, is only indirectly referred to, while the later and minor intrusions of gabbro and diabase are not discussed at all. Magmatic assimilation as a prime cause of the variations of the later gabbro has been discussed at some length in a recent paper by the writer.²

FACIES OF THE GREAT SYENITE-GRANITE INTRUSIVE BODY

GENERAL OBSERVATIONS

With certain possible rather local exceptions, the great masses of syenite and granite, which are the most abundant rocks in the Adirondack region, are regarded as belonging to a single, vast intrusive body. Evidences for this view are presented below. What may be regarded as a normal quartz syenite shows, on the one hand, facies which are basic and really of dioritic or even gabbroic composition, while, on the other hand, there

² W. J. Miller: Variations of certain Adirondack basic intrusives. *Jour. Geol.*, vol. 21, 1913, pp. 160-180.

are variations ranging through granitic syenite to true granite. The prevailing rock is syenite to granitic syenite. Brief descriptions only are here given, the reader being referred to various papers and bulletins of the New York State Museum for details.

NORMAL SYENITE

This rock shows a greenish-gray color when fresh and it weathers to a light brown. Its weathered surface is seldom more than a few inches thick. As regards structure and granularity, it is a quite variable rock. The granularity ranges from fine to fairly coarse, with a medium grain decidedly prevalent. A porphyritic texture is sometimes moderately developed. The structure ranges from only faintly gneissoid to very clearly gneissoid to almost schistose, this structure being accentuated by the arrangement (or flattening) of the dark-colored minerals with their long axes parallel to the direction of the foliation. Evidence of crushing or granulation is common, though it varies greatly, the feldspars showing the effects of the granulation more than the other minerals.

In mineral composition, too, the syenite is rather variable. Feldspars—microperthite, orthoclase, and soda-rich plagioclases—constitute 50 to 80 per cent of the rock. Quartz, in varying amounts up to 20 per cent, is always present. Pyroxene or hornblende, or both, occur in amounts up to 20 per cent. The pyroxene is mostly a green augite, with sometimes a little hypersthene. Hornblende is generally more abundant than pyroxene in the more quartzose syenites. From 1 to 5 per cent of magnetite always appears. Small amounts of zircon, zoisite, and apatite seldom fail. Garnet is much more sporadic in occurrence, though at times it makes up several per cent of the rock.

BASIC PHASES OF THE SYENITE

So far as known, these rocks are of comparatively little extent in the Adirondack region. By relative increase in plagioclase and decrease in quartz the normal syenite shows transitions to rocks of dioritic or gabbroic composition. At times the plagioclase is the only feldspar present, and quartz is either wholly absent or present in only slight amount. Hornblende or pyroxene (augite or hypersthene), or both, always appear in amounts up to 20 per cent. From 1 to 6 per cent of magnetite nearly always occurs. Smaller amounts of biotite, apatite, zircon, and zoisite usually appear, while garnet is of sporadic occurrence.

As regards color, granularity, and structure the statements made for the normal syenite apply almost equally well here.

GRANITIC SYENITE

By increase in quartz content to from 20 to 25 per cent the normal syenite passes into what may be called granitic syenite. Microcline often occurs in considerable quantity. Biotite usually occurs in amounts up to 8 or 10 per cent, and sometimes it appears to be secondarily derived from hornblende. Pyroxene has not been noted in this rock. The color varies from gray or greenish gray to pink or almost red, this red color apparently being due to hematite specks or stains. In all other respects the granitic syenite is much like the normal syenite.

GRANITE AND GRANITE PORPHYRY

The granite and granite porphyry represent the most acidic phases of the great syenite-granite body, and these show perfect gradations through granitic syenite to normal syenite. Arbitrarily the rocks are called granite when the quartz content exceeds 25 per cent.

The colors range through greenish gray, light gray, pink to almost red, with pink or red granites most common. Compared with the normal syenite, these granites have almost invariably smaller amounts (usually only 5 to 10 per cent) of dark-colored minerals; frequently considerable amounts of microcline, in addition to micropertite, orthoclase, and plagioclase; much more quartz; generally less hornblende or none; no pyroxene, and almost constant presence of biotite (or muscovite) up to 15 or 16 per cent. In all other respects the granite is like the normal syenite or granitic syenite, while the granite porphyry differs from the granite only in its very distinct porphyritic texture.

The so-called "Laurentian granite" of the Thousand Islands region is in no essential particular different from the granite here described.

DIFFERENTIATION OF THE SYENITE-GRANITE MAGMA

ACTUAL EXAMPLES

Observations of C. H. Smyth, Jr.—In an important paper dealing with the rocks of the western Adirondack region, Smyth says, concerning the syenite (called gabbro³ in this paper):

"Different specimens of the rock require, from a strictly petrographic point of view, different names, ranging from gabbro and anorthosite to augite-syenite. . . . They are different portions of a single intrusive mass and owe their differences to magmatic variations."⁴

³ In later papers by Smyth the rock is called syenite instead of gabbro, and it is now known to be identical with the great bodies of syenite so common in the Adirondack region.

⁴ C. H. Smyth, Jr.: Bull. Geol. Soc. Am., vol. 6, 1895, pp. 271 and 274.

Again, in the same paper he proves that the normal syenite shows a gradual transition into a red granitic gneiss. He says:

"Between this village (Natural Bridge) and Carthage, 10 miles west, the country is occupied by a red (granitic) gneiss, rather fine grained, and not, as a rule, strongly foliated. Starting from the normal gabbro (syenite) at Natural Bridge and passing toward this red gneiss the natural expectation, based on the appearance of the two rocks, would be to find the one cutting, or superimposed on, the other; but such is not the case. On the contrary, about two miles west of the village the gabbro (syenite) undergoes a conspicuous modification. It becomes gradually finer grained and gneissoid and changes from gray to red. In other words, it passes gradually into the red gneiss, which must therefore be regarded as a modified portion of the gabbro (syenite)."⁵

He says the transition zone is about half a mile wide. He then describes a similar transition, but where the red gneiss is much coarser grained and contains considerable hornblende.

These careful observations made upon large rock masses clearly establish the fact that here at least a whole series, ranging from gabbro through syenite to red granite, has been produced by magmatic differentiation. The writer believes this to be a capital point as applied to the Adirondack region in general, for many more recent observations have shown this sort of differentiation to be common.

Observations of H. P. Cushing.—Cushing, in his description of the Franklin County syenite, says:

"All intermediate stages between granite and syenite may be found, so that there is evidently a passage of one rock into the other. These granites are either red or green in color, and while very quartzose and poor in dark silicates these are the same as appear in the syenites, and the quartz has the same spindle form."⁶

In his description of the syenite of the Long Lake quadrangle, Cushing writes:

"The rock is exceedingly variable, much more so than is the anorthosite. All the varieties grade into one another, so that any separation in mapping is an arbitrary matter. . . . The variations of the rock are in two main directions. In the one case the dark-colored minerals increase in quantity at the expense of the feldspar, garnet appears, and quartz diminishes and disappears. The syenite passes into a monzonite and ultimately into a shonkinite. . . . In the other direction the rock changes by increasing quartz. . . . The feldspar also changes slightly and tends to become red instead of green, pro-

⁵ *Ibid.*, pp. 282-283.

⁶ H. P. Cushing: 18th Ann. Rept. N. Y. State Geologist, 1898, p. 106.

ducing green and red mottled rocks. Finally, the red predominates and the rock becomes a distinct granite."⁷

Observations of I. H. Ogilvie.—Ogilvie states, concerning the syenite and granite of the Paradox Lake quadrangle, that—

"Both in this region and elsewhere the syenite is bordered by granite, the granite being much more gneissic than the syenite. Gradations between the two are common. It seems most reasonable to regard the granite as a border development of the syenite, derived from the same magma."⁸

Observations of J. F. Kemp.—Kemp says of the syenite series of the Elizabethtown and Port Henry quadrangles:

"There are phases, apparently differentiation products of the syenite magma, in which it (quartz) is very abundant, and the rock becomes a (reddish) granite or of granitic composition. . . . Again, in the basic extremes, it fails, and in the true syenite phases, the most characteristic of the series, it is rare or absent."⁹

Observations of the writer.—The writer has made many observations on differentiation throughout the southern Adirondack region, but only a few of the most decisive, carefully studied examples will here be mentioned.

In the Port Leyden quadrangle¹⁰ the normal syenite clearly grades into a red granitic gneiss, it being impossible to draw sharp lines of separation between them in the field. It seems certain that this red granitic gneiss is a differentiation phase of the normal syenite. Except for the greater granulation, somewhat higher quartz content, and red hematite stains of the granite, microscopic study shows no essential difference between the two rocks.

In the Broadalbin quadrangle,¹¹ west of Sacandaga Park, a typical pink granite porphyry, with prominent porphyritic texture, high quartz content, presence of biotite and absence of hornblende, grades into a typical, medium grained, moderately quartzose hornblende syenite. The clearly exhibited field relations, microscopic study of the transition rocks and very closely related chemical compositions prove that these two rocks, so different in appearance, are really only differentiation products from the same cooling magma.

In the Lake Pleasant quadrangle¹² the writer has studied, in the field

⁷ H. P. Cushing: N. Y. State Mus. Bull. 115, 1907, pp. 477-478.

⁸ I. H. Ogilvie: N. Y. State Mus. Bull. 96, 1905, p. 503.

⁹ J. F. Kemp: N. Y. State Mus. Bull. 138, 1910, pp. 46-47.

¹⁰ W. J. Miller: N. Y. State Mus. Bull. 135, 1910, pp. 15 and 17.

¹¹ W. J. Miller: N. Y. State Mus. Bull. 153, 1911, pp. 18 and 20.

¹² W. J. Miller: Geology of the Lake Pleasant Quadrangle; in preparation.

and by means of thin sections, a fine example of gradation from a basic or gabbroic phase of the syenite to a pink granite. Beginning one-fourth of a mile northeast of the top of Mount Francisco, and passing a half mile southwestward over the mountain top, one may observe the transition from a gabbroic rock through normal syenite and granitic syenite into a pink granite. There is a progressive diminution of dark-colored minerals from 19 per cent to $31\frac{1}{2}$ per cent. From the normal syenite to the granite the exposures are perfectly continuous, and to the basic syenite they are nearly so. Evidently this is a clear case of magmatic differentiation.

Also in the Lake Pleasant quadrangle, Groff Mountain consists of a mass of typical gray syenite porphyry which, toward the west, becomes more quartzose, less porphyritic, and grades through granitic syenite into pink granite, while toward the south it merely loses its porphyritic texture and passes into normal syenite. Thus we have here still other types of differentiation illustrated.

In the North Creek quadrangle the writer has frequently observed the normal syenite passing by perfect gradations through granitic syenite to gray or red granites on the one hand or granite porphyry on the other. Most of these variations, at least, are very clearly only different phases of the same great intrusive body.

GENERAL CONSIDERATIONS

In order to more clearly emphasize the great similarity in chemical composition of the members of the syenite-granite series, the following chemical analyses of typical members of the series from various portions of the Adirondacks are here presented in tabular form:

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	54.10	61.01	62.41	63.45	64.47	66.35	66.72	68.50	70.13	71.45	73.10
Al ₂ O ₃	17.45	15.36	18.75	18.38	10.51	14.09	16.15	14.69	15.47	13.83	14.29
Fe ₂ O ₃	4.52	2.98	2.49	1.09	1.11	1.81	1.23	1.34	1.52	1.10	1.04
FeO	6.47	7.77	4.91	2.69	7.37	4.49	2.19	3.25	1.05	1.91	1.04
MgO	2.33	0.78	0.61	0.35	5.21	1.05	0.73	0.26	0.85	0.56	0.53
CaO	6.17	4.05	3.17	3.06	3.10	3.16	2.30	2.20	1.60	1.44	1.18
Na ₂ O	3.81	3.68	3.09	5.06	2.21	3.32	4.36	3.50	3.72	2.62	3.08
K ₂ O	3.06	3.90	4.25	5.15	3.63	4.08	5.66	5.90	4.39	6.09	5.36
H ₂ O	0.57	0.49	0.41	0.30	0.93	0.35	0.77	0.40	0.49	0.32	0.61
TiO ₂	0.19	.....	.....	0.07	.....	1.00	.....	.....	0.30	0.42	0.18
P ₂ O ₅	0.88	.....	.....	.....	0.25	0.40	.....	0.03	.....	0.03	0.03
MnO	0.35	0.08	.....	trace	.....	0.17	0.07	0.10	0.08	0.17	0.07
S	0.14	.....	.....	.....	0.12	0.04	.....	.....	0.07	0.02	0.02
Cl .....	.....	.....	.....	.....	.....	0.02	.....	.....	0.05	0.03	0.03
F	0.05	.....	.....	.....	.....	0.03	.....	.....	0.09	0.01	0.02
BaO	0.10	.....	.....	0.13	.....	0.03	.....	0.05	0.05	0.02	.....
ZrO .....	.....	.....	.....	.....	.....	trace	.....	.....	.....	0.02	.....
CO ₂ .....	.....	.....	.....	.....	0.58	.....	.....	.....	.....	.....	.....
	100.19	100.10	100.09	99.73	99.49	100.39	100.18	100.22	99.86	100.04	100.58

1. Basic syenite (andose near shoshonose) from near Raquette Falls. E. W. Morley, analyst. Described by H. P. Cushing, New York State Museum Bulletin 115, pages 513-514.

2. Augite-syenite (harzose), $3\frac{1}{2}$ miles north of Tupper Lake Junction. E. W. Morley, analyst. Described by H. P. Cushing, New York State Museum Bulletin 115, pages 514 and 516.

3. Augite-syenite (adamellose). Ticonderoga, Essex, County. M. K. Adams, analyst. Described by J. F. Kemp, New York State Museum Bulletin 138, pages 45-46.

4. Augite-syenite (pulaskose). Loon Lake, Franklin County. E. W. Morley, analyst. Described by H. P. Cushing, Geological Society of America Bulletin, volume 10, pages 177-192.

5. Syenite (adamellose). Whitehall, New York. W. F. Hillebrand, analyst. Described by J. F. Kemp, New York State Museum Bulletin 138, pages 45-46.

6. Quartz-hornblende syenite (adamellose). One mile northwest of Northville. E. W. Morley, analyst. Described by W. J. Miller, New York State Museum Bulletin 153, pages 14-17.

7. Augite-syenite (toscanose). Little Falls, New York. E. W. Morley, analyst. Described by H. P. Cushing, New York State Museum Bulletin 115, pages 514-515 and page 518.

8. Quartz-syenite (toscanose). Two and one-half miles south of Willis Pond, Altamont, Franklin County. E. W. Morley, analyst. Described by H. P. Cushing, New York State Museum Bulletin 115, pages 514 and 519.

9. Laurentian granite (toscanose). Two miles east of Theresa. E. W. Morley, analyst. Described by H. P. Cushing, New York State Museum Bulletin 145, pages 176-177.

10. Biotite-granite porphyry (toscanose). One and three-fourths miles north-northwest of Northville. E. W. Morley, analyst. Described by W. J. Miller, New York State Museum Bulletin 153, pages 17-20.

11. Laurentian granite (toscanose). One-fourth of a mile south of Alexandria Bay. E. W. Morley, analyst. Described by H. P. Cushing, New York State Museum Bulletin 145, pages 176-177.

Considering the pronounced textural and mineralogical variations of these rocks and their wide distribution in the Adirondack region, they show decidedly close chemical relationships as indicated by their positions in the quantitative system. Thus, while some are persalanes and some dosalanes, this difference is very largely due simply to the variations in quartz and feldspar contents and, even so, several of the rocks are close to the border between the two classes. In their respective classes all these rocks fall in order 4 or 5, rang 2 or 3, and subrang 3 or 4. Such close chemical relationships of the members of the great syenite-granite series strongly corroborates the conclusion reached by field and microscopical study, that the syenite-granite series represents a single great intrusive body.

Is any of the granite of the Adirondack region to be classed with the so-called "Laurentian granite" of the Thousand Islands district, and recently regarded by Cushing as older than the great mass of Adirondack syenite? He says:

"Whether these Laurentian granites are recognizable, however, over any considerable part of the Adirondack region, in distinction from granites of later date, is a much less certain matter, though we believe it to be the case."¹⁸

This is an important question which should be constantly kept in mind in field work. So far as can be gathered from the descriptions of the Thousand Islands granite and syenite, there appears to be no positive evidence that the so-called Laurentian granite is actually older than the syenite. In the detailed surveys by the writer of five or six quadrangles scattered over the southern Adirondack region, areas of gray to red granites, much like the so-called Laurentian granite in composition and appearance, have frequently been met with. Compare, for example, the analyses of the Laurentian granites of the Thousand Islands district with the analyses of other acidic rocks from the syenite-granite series in the above table. In not a single case has any positive evidence been forthcoming to show that any of the Adirondack granites are distinctly older than the syenite, while many times the granites are clearly only acidic variations or phases of the normal syenite. A few only of such definitely proved variations have been given above. Of course this does not preclude the possible presence of really older granites in these regions, because by no means all of the red granites demonstrably grade into syenite on account of lack of proper exposures. In the face of the fact, however, that so much detailed work has been done by various geologists, it seems little short of remarkable that if there are really two great intrusive bodies—one of granite and the other of syenite—of distinctly different ages, no proof has been obtained. If any such older granite does exist, it must be small in amount, and the writer believes it could rarely be successfully mapped as a formation distinct from the granites, which are certainly only phases of the syenite.

In the light of present knowledge the writer believes that if the term "Laurentian" is used at all in northern New York, it should be applied to the large bodies of syenite as well as granite for, with comparatively slight possible exceptions, these rocks represent merely different phases of what was a single great intruding magma. In this connection it is interesting to note that, in their reference to the Laurentian series of the

¹⁸ H. P. Cushing: N. Y. State Mus. Bull. 145, 1910, p. 38.

Penokee-Gogebic district of Michigan and Wisconsin, Van Hise and Leith say:

"In general, in the district under discussion, the granites are of a somewhat acidic type. However, in the central area besides the granites there are syenites and even gabbros, and the three rocks seem to grade into each other."¹⁴

Similar statements are made for the Vermilion district of Minnesota. In both of these districts the Laurentian series shows variations much like those of what the writer regards as a single syenite-granite intrusive body in the Adirondacks.

Even though syenite should in a few places be found cutting granite, or granite cutting syenite, it would not necessarily prove the younger age of the syenite in the one case or of the granite in the other, except in a local and very restricted sense. Thus a granitic portion of the magma may have consolidated or become very viscous, after which a still molten portion of more syenitic composition was injected into the granite. Likewise it is by no means inconceivable that a solidified or very viscous syenitic portion may have been intruded by a still molten portion of granitic composition. Slight local differences in age would thus result, but, without other proof, we should not be justified in concluding that the great mass of granite is distinctly older than the great mass of syenite or vice versa. This is an important consideration, so that the finding of an occasional example of syenite cutting granite or vice versa would not necessarily vitiate the conclusion that the great bodies of Adirondack syenite and granite are merely differentiation phases of the same great intrusive magma.

Such an explanation of possible occurrences is, however, not needed to help the writer out of a dilemma, because the surprising fact is that, in spite of so many detailed observations by several workers, no definite case of syenite cutting granite has been found and, so far as the writer is aware, but one good case of granite cutting syenite is known. This latter is Cushing's "Morris granite," which, in small masses, cuts syenite in the Long Lake quadrangle.¹⁵

It is interesting to note that this very "Morris granite" illustrates the principle just set forth, for, as Cushing says, it shows both a fine-grained and a coarse-grained phase, with the coarse not only cut by the fine but also grading into it.

Similar cases of slight differences in age of the same intrusive magma have been observed in connection with some of the later gabbros and dia-

¹⁴ Van Hise and Leith: U. S. Geological Survey Monograph 52, 1911, p. 226.

¹⁵ H. P. Cushing: N. Y. State Mus. Bull. 115, 1907, p. 482.

bases, which are either less or not at all metamorphosed, and hence show relationships more clearly. Thus, in the North Creek quadrangle, the writer has observed in a gabbro dike $1\frac{1}{4}$ miles a little west of south of South Horicon fairly coarse-grained gabbro in sharp contact with fine-grained gabbro, the latter gradually becoming coarser again away from the contact, and clearly showing a second intrusion of rock much like the first after the first had partly or wholly solidified. Also Kemp says, concerning a diabase dike of the Elizabethtown quadrangle:

"One very interesting case has been found of one dike penetrating another and chilled by it. There were clearly two periods of intrusion in this instance, and one followed long enough after the other to have permitted the first to quite thoroughly cool."¹⁶

Such actual examples of separate intrusions of the same magma strongly support the idea that similar things might be expected in connection with the larger syenite-granite magma.

Twenty years ago Barlow said, concerning certain granite and granite gneisses north of Lake Huron, that these rocks frequently grade into each other, while in some cases granite cuts the gneiss. After giving detailed reasons, he concluded that:

"These masses of granite may therefore be regarded as non-foliated areas of gneiss, representing simply certain eruptions from the same fluid magma from which the gneiss itself has solidified, and although a sufficient time had elapsed to allow of more or less complete consolidation of the gneiss, yet they represent the same age in geologic time."¹⁷

ASSIMILATION BY THE SYENITE-GRANITE MAGMA

ACTUAL EXAMPLES

Observations of C. H. Smyth, Jr.—In his description of Grenville gneiss inclusions, from a few feet to a few rods across, in the western Adirondack region, Smyth says:

"Some of these inclusions are clearly defined with sharp boundaries, but others are blended with the surrounding syenite as though they had undergone a partial melting."¹⁸

Again, in a recent paper on the pyrite deposits of Saint Lawrence County, Smyth says:

"It often happens that a rock is of composite character as a result of injection or assimilation, giving, on the one hand, a sediment more or less 'soaked'

¹⁶ J. F. Kemp: N. Y. State Mus. Bull. 138, 1910, p. 58.

¹⁷ A. E. Barlow: Bull. Geol. Soc. Am., vol. 4, 1893, p. 315.

¹⁸ C. H. Smyth, Jr.: 18th Ann. Rept. N. Y. State Geologist, 1898, p. 477.

with igneous material and on the other an igneous rock which has melted into itself or assimilated sedimentary material. Between these two types every gradation exists."¹⁹

No details, however, are given.

Observations of H. P. Cushing.—Cushing states that the differentiation of the basic border phase of the Tupper syenite of the Long Lake quadrangle

"seems conditioned on the nature of the bordering rock. The most of the basic syenite and all of the more gabbroic of it is in close association with the anorthosite gabbro border."²⁰

"These relations are readily explained on the assumption that there has been actual incorporation and digestion of material from the surrounding rocks by the syenite, and that the digestion has been mainly a border phenomenon. Nothing that was observed is antagonistic to such an explanation. No other solution that will account for the observed relations suggest itself."²¹

Still more recently, Cushing has clearly recognized the influence of magmatic assimilation in the Thousand Islands region. He says:

"The granite dikes usually represent the extreme acid state of the rock (Laurentian granite). The main mass averages less acid, chiefly because of the inclusions (amphibolite) and the attack of the granite on them. In its preliminary stages this usually takes the form of an injection of the granite in thin sheets along the foliation planes of the amphibolite, the so-called 'lit-par-lit,' or leaf type of injection. . . . Then, here and there the granite breaks out from the foliation planes and spreads through the rock adjacent. . . . This process becomes more and more pronounced, until much of the rock is broken up into a granular mosaic of particles cemented together by granite films, producing what may be called a mosaic type of injection. . . . As a further stage in both types of injection the sharp boundaries become blurred, and this shading of the two rocks into one another becomes more and more prominent, until finally rocks result, which seem unquestionably to be due to the complete digestion of the amphibolite by the granite, gray gneisses of intermediate composition."²²

Observations of the writer.—A large number of actual examples of magmatic assimilation have come under the writer's observation, but with few exceptions these are all of small areal extent. The purpose is to describe only a few of the most typical and carefully studied examples, or just enough to make clear the nature of the evidence and the character and extent of the resulting rocks.

The most frequently occurring cases are those of small Grenville inclu-

¹⁹ C. H. Smyth, Jr.: N. Y. State Mus. Bull. 158, 1912, pp. 143-144.

²⁰ H. P. Cushing: N. Y. State Mus. Bull. 115, 1907, p. 479.

²¹ H. P. Cushing: Bull. Geol. Soc. Am., vol. 18, 1907, p. 484.

²² H. P. Cushing: N. Y. State Mus. Bull. 145, 1910, p. 37.

sions, from a few feet to a few rods long, which have been either partially or wholly fused and melted into the syenite or granite. Very fine examples occur $1\frac{1}{2}$ miles northeast of the summit of Kelm Mountain (North Creek quadrangle),²³ where inclusions of dark, garnetiferous, Grenville gneiss show perfect gradations, through zones of a few feet, into the inclosing granite porphyry. The intermediate rock is coarse grained, very garnetiferous, and not so porphyritic as the true granite porphyry.

Another example, typical of many similar occurrences, is a single rock ledge, 40 feet across, 1 mile due southeast of the summit of Hamilton Mountain (Lake Pleasant quadrangle), where the intimate relationships of dioritic, granitic syenitic, granitic, and Grenville gneisses are clearly exhibited. In the accompanying table the compositions of these gneisses, except the Grenville, are shown:

Slide No.	Orthoclase.	Micro-perthite.	Olig.-And.	Quartz.	Biotite.	Horn-blende.	Hyfers-thene.	Magnetite.	Zoisite.	Zircon.	Titanite.
24	5	.....	55	13	7	18	.....	1	1	little	... ..
23	45	.....	23	22	3	.....	5	$1\frac{1}{2}$	$\frac{1}{2}$	little	.....
21	25	38	5	27	8	.....	.....	1	$\frac{1}{2}$	$\frac{1}{2}$	little

Number 24 is a rather basic (dioritic) rock greatly resembling certain phases of basic syenite; number 23 is a granitic syenite, and number 21 is a good pink granite. These types grade back and forth into each other several times in this one outcrop. There are many narrow streaks, layers or inclusions of Grenville dark, biotite-feldspar gneisses sometimes containing garnets. At times these streaks are pretty clearly defined, while again they are not, but always, though often locally twisted, they roughly follow the gneissic bands. The texture and composition, especially of the granite, vary considerably, and a few garnets occur sporadically in the syenite and granite. The ledge is perfectly bare, with relationships well exhibited, and it is certain that the dark, dioritic bands or streaks are Grenville which have been more or less fused into the molten granite. Where thoroughly assimilated, the basic rocks have resulted, and where not thoroughly fused in the streaks are still visible. Every stage of the assimilation process is shown.

²³ W. J. Miller: N. Y. State Mus. Bull. 170, 1914, p. 23.

Similar phenomena exhibited on a much more extensive scale may be seen in excellent outcrops along the creek from one-fourth to one-half mile below Dunning Pond (Lake Pleasant quadrangle). The variable red, granitic gneiss is so full of gray Grenville inclusions as to make up a considerable percentage of the rock. There are all stages, from thoroughly fused in or assimilated Grenville to some which has been but little affected.

A very definite case of the assimilation of the border of a large Grenville gneiss inclusion by the inclosing syenite is shown at the Rogers garnet mine²⁴ on Gore Mountain (Thirteenth Lake quadrangle). This inclusion, which has a length of three-fourths of a mile and a maximum width of 100 feet, consists of a medium grained hornblende-garnet gneiss. This typical garnet-bearing rock (number 1 of the table below) passes by perfect gradation through an 8-foot or 10-foot zone into a basic syenite or acidic diorite (number 2 of the table), which contains distinct dodecahedral garnet crystals up to an inch or more across. This rock, in turn, grades into a hornblende (quartzless) syenite (number 3 of the table) which merges into the typical country rock of quartz-hornblende syenite, these two latter rocks being at times somewhat garnetiferous. This transition zone has certainly been formed by assimilation or actual fusing together of the syenite and the border of the great inclusion at the time of the intrusion.

	Orthoclase.	Plagioclase.		Horn- blende.	Biotite.	Hypers- thene.	Magnetite.	Zoisite.	Apatite.	Pyrite.
1	20	Lab.	20	40	3	15	1	1	.....	.....
2	30	Ol. An.	30	36	.....	.....	1	2	little	1
3	50	An.	25	24	.....	.....	.....	1	little	.....

At the Hooper garnet mine, just east of the northern end of Thirteenth Lake, the whole mass of rock mined is almost precisely like the transition rock just described. All evidence points to the origin of this Hooper mine rock as due to pretty thorough melting of an admixture of syenite and Grenville sediment where the Grenville inclusion was perhaps deeper down in the magma, or possibly a number of smaller hornblende gneiss inclusions, maybe with some limestone, were assimilated by the molten syenite.

²⁴ W. J. Miller: Econ. Geol., vol. 7, No. 5, 1912, p. 500.

A Grenville inclusion, one-half mile long and well exposed in the bed of Elbow Creek, $1\frac{1}{2}$ miles north of Wells (Lake Pleasant quadrangle), consists chiefly of dark hornblende-garnet gneiss. Its borders are clearly fused by the inclosing normal syenite giving rise to peculiar looking rocks of distinctly intermediate character.

On the eastern shore of the lake, $1\frac{3}{4}$ miles northeast of Long Lake village (Blue Mountain quadrangle), a pink granite very distinctly grades into a wide band of biotite-quartz Grenville gneiss.

Magmatic assimilation on larger scales, however, is to be best observed in areas of so-called "mixed gneisses." These are really areas of Grenville which have been all cut to pieces, and in some cases more or less fused by the intrusive magmas. In some areas true Grenville rocks predominate; in others true igneous rocks prevail; while in still others the most common rock appears to be of intermediate character due to an actual melting and incorporation of Grenville sediments by the intrusives. Except along fault lines, these mixed gneisses everywhere grade into either true Grenville or syenite or granite, and the drawing of boundary lines is largely a matter of personal judgment.

On such a larger scale, good examples of rocks of intermediate character make up much of the mixed gneiss area which lies just east of Chestertown²⁵ (North Creek quadrangle). Thus the whole top of Prospect Mountain consists of gray, fine grained, very massive rock which has the composition of a biotite granite. This rock is pretty homogeneous except for occasional patches or stringers of gray Grenville gneisses which are fused into the mass. Passing southward and southwestward down the mountain side, this rock grades perfectly into a medium grained, biotite granite which contains very few Grenville inclusions, and this rock, in turn, grades perfectly into the typical biotite granite porphyry at the base of the mountain. Passing westward down the mountain side, however, the fine-grained granitic rock at the top gradually becomes coarser grained and contains more numerous and more clearly defined inclusions of Grenville gneisses, with these rocks, in turn, grading into pure biotite-garnet and quartzitic Grenville gneisses at the base of the mountain. Thus we have a perfect transition from the gray, granitic rock into the granite porphyry on the one hand and into the Grenville on the other, so that there appears to be no escape from the idea that these gray, granitic rocks were formed by actual fusion and incorporation of more or less of the Grenville into the granite porphyry magma. The presence of the inclusions does not necessarily oppose this view, because

²⁵ W. J. Miller: N. Y. State Mus. Bull. 170, 1914, pp. 23-24.

they may well enough simply represent fragments of Grenville which were caught in the granite magma just before consolidation, or when the temperature was not high enough to actually melt the fragments. Gray granitic rocks of apparently the same origin are common throughout this mixed gneiss area, which occupies about 2 square miles.

Another interesting mixed gneiss area is the one just north of the village of Horicon²⁶ (North Creek quadrangle). In the vicinity of the quarry at the base of the mountain the rock is very typical granite porphyry, which contains a few long, narrow, sharply defined Grenville gneiss inclusions. Going up the mountain side from the quarry the granite porphyry, which at times (in patches or wide bands) appears typical, is intimately associated with Grenville. This Grenville occurs as large and small inclusions, often sharply defined and nearly always drawn out parallel to the foliation. The included rocks are chiefly banded biotitic, hornblendic, and quartzitic gneisses often in bands from 20 to 30 feet wide. Toward the top of the mountain the rock is mostly like the gray granitic rock already described as occurring at the top of Prospect Mountain, and the inclusions are fewer and not so sharply defined. Here again this granitic gneiss appears to be an assimilation product, while farther down the mountain side the temperature seems not to have been high enough to cause any considerable melting or assimilation of the included gneisses.

Excellent exposures in an open field between Blue Mountain Lake village and Crystal Lake (Blue Mountain quadrangle) afford a practical demonstration of the very intimate relations of granitic and Grenville gneisses with intermediate rocks due to more or less assimilation. The granites are pinkish to grayish and rather variable. In certain outcrops Grenville gray, biotitic or dark garnetiferous or pyroxenic gneisses may be seen to grade into the igneous rock with no visible contacts. In a few cases contacts are fairly sharp. Most of the exposures, however, consist of rocks of intermediate character, clearly the products of assimilation.

An area of what is regarded as a basic (gabbroic) phase of normal syenite extends from Speculator Mountain to Indian Head Mountain (Lake Pleasant quadrangle), showing a length of 5 miles and a maximum width of $1\frac{1}{2}$ miles. The most typical rock contains 75 to 80 per cent oligoclase to labradorite; 6 to 9 per cent pyroxene (usually augite); 3 to 10 per cent hornblende; 1 to 4 per cent magnetite; 0 to 5 per cent garnet; 0 to 2 per cent biotite, and usually slight amounts of zoisite or apatite. In some places the rock looks very gabbroic, and in others much like cer-

²⁶ W. J. Miller: N. Y. State Mus. Bull. 170, 1914, p. 24.

tain basic border phases of the Essex County anorthosite. Much of the rock, however, looks much like the normal syenite, though it is always without quartz. The degree of foliation varies considerably, though it is generally pronounced. The clear red garnets are not thought to be of secondary origin. Along the borders, especially to the east and southeast, the rocks of this area grade into normal quartz-syenite. This area of so-called basic syenite appears to have been produced by magmatic assimilation where dark, basic Grenville gneisses were incorporated into the normal syenite magma. A considerable inclusion, one-half mile southeast of the southern end of Lake Pleasant, has an important bearing in this connection. The inclusion contains 40 per cent hornblende; 30 per cent oligoclase to labradorite; 18 per cent hypersthene; 1 per cent garnet, and 2 per cent magnetite and pyrite. Its borders have been well fused, and the assimilation product greatly resembles the most typical phase of the syenite just to the west. A complete assimilation of many such basic Grenville fragments by the normal syenite magma would certainly account for the so-called basic syenite. The view that the syenite magma did break through and actually assimilate considerable quantities of such Grenville rocks is strongly supported by the following facts: The very presence of the above-mentioned inclusion, which is taken to represent a late stage in the stoping and assimilation process; the fact of the former existence of much basic Grenville gneiss over the site of the basic syenite area as proved by numerous inclusions and the present occurrence of large masses just northward; the variable composition and appearance of the rock which would be expected because of differences in amount and character of the rocks assimilated; the gradation of the basic syenite into normal syenite; and the fact that the rocks so very closely resemble rocks definitely known to have been produced by the action of a similar syenite magma upon similar Grenville rocks in the Thirteenth Lake quadrangle (see description above).

GENERAL CONSIDERATIONS

The widely different views held by petrologists regarding magmatic assimilation are suggested by the following brief references to several recent papers.

Loewinson-Lessing believes that assimilation of invaded rock has a great influence upon differentiation, and says:

"Is not assimilation a phenomenon that must be expected *a priori* in intrusive bodies, for it is difficult to imagine a magmatic basin heating the rocky masses in contact with it for a long period without partly dissolving them."²⁷

²⁷ F. Loewinson-Lessing: *Geol. Mag.*, n. s., Dec. V, VIII, 1911, pp. 248-257, 289-297.

A few years ago Daly²⁸ worked out an elaborate magmatic stoping and assimilation hypothesis according to which the intrusions of many great acidic, batholithic magmas have been accompanied by extensive assimilation of stoped blocks of invaded rock.

Van Hise²⁹ admits that cases of local fusion or absorption of fragments or borders of invaded rocks by intruding magmas are known, but he does not believe any proved case of fusion on a large scale is known. Referring to Lawson's³⁰ work in the Rainy Lake and Lake of the Woods districts of Canada, Van Hise dissents from the view that extensive or so-called "subcrustal" fusion of the invaded rocks has been proved for those districts.

Adams and Barlow,³¹ in an elaborate report on the Haliburton and Bancroft areas of Ontario, say:

"The further question as to how far granite, having caught up inclusions of the rock through which it breaks in the manner described, dissolves, digests, or further acts on them, is one on which it is more difficult to get conclusive evidence. That it does so in some cases is certain."

They describe several examples where, rather locally, the granite magma has been rendered basic by the solution of amphibolite in it; but they say that undisputed evidence of such solution on an extended scale has not yet been obtained. The conclusions reached by these two geologists regarding this Canadian region are of particular interest as compared with the writer's conclusions regarding the Adirondacks, since the geological conditions are so similar in these two regions.

Cross,³² in a review of certain petrological papers, states:

"That many magmas represented in rocks open to investigation came from depths where the conditions of fusion and assimilation existed is seemingly incontestable. . . . But the assumption that assimilation has taken place generally in large intrusive bodies at contacts now visible is not plain to many petrologists."

Iddings,³³ in his book on Igneous Rocks, states that:

"Evidences of absorption by the igneous magma of material from adjoining rocks are very slight, even in cases where these rocks have been profoundly

²⁸ R. A. Daly: *Amer. Jour. Sci.*, vol. xv, 1903, pp. 269-298; *ibid.*, vol. xvi, 1903, pp. 107-126; *ibid.*, vol. xxvi, 1908, pp. 17-50.

²⁹ C. R. Van Hise: *U. S. Geological Survey Monograph XLVII*, 1904, pp. 730-735.

³⁰ A. C. Lawson: *Bull. Geol. Soc. Am.*, vol. 4, 1890, pp. 185-186.

³¹ F. D. Adams and A. E. Barlow: *Department of Mines, Canada, Memoir 6*, 1910, pp. 116-117 and 122-123.

³² W. Cross: *Jour. Geol.*, vol. 20, 1912, p. 364.

³³ J. P. Iddings: *Igneous rocks*, 1909, p. 282.

affected by the intruded magma. . . . It appears from a study of intruded igneous rocks that they were not sufficiently heated to melt or dissolve invaded rocks to any appreciable, or at most to any considerable, extent."

Some of the facts very favorable to magmatic assimilation in the Adirondack region are the following:

- (1) The tremendous masses of the syenite-granite intrusive body;
- (2) The vast number of masses of Grenville rocks which were either actually caught up as inclusions or almost completely enveloped by the magma, these masses ranging in size from an inch or less in width and a foot or two long, to others some miles wide and many miles long;
- (3) The very deep-seated conditions under which the Grenville rocks were intruded by the magma; and
- (4) The at least frequent highly fluid character of the magma, as shown by the very intimate and minute penetration of certain of the invaded rocks by the magma.

That the stopping and engulfment of such small to large Grenville masses by the tremendous body of intruding magma were very common processes throughout the Adirondack region is abundantly established by recent detailed geological surveys. Also that many of these masses must have sunk deep into the magma is proved by the persistent occurrence of such inclusions throughout the region, irrespective of existing differences of thousands of feet of altitude and the variable amount of the profound denudation to which this region has been subjected.

In spite of these very favorable conditions, there is no positive evidence whatever that great bodies of the Adirondack syenitic or granitic magma have been appreciably changed in composition due to the incorporation or assimilation of Grenville gneisses or other rocks. As the above described examples show, however, magmatic assimilation has been of common occurrence, but always of pretty local extent. Of the large number of definitely known cases very few involve areas as large as a few square miles, while by far most of them involve masses or belts only a few feet or rods in width and less than a mile in length.

The differential character of the assimilation process is also noteworthy. Thus at one place there will be unquestioned evidence of assimilation, while within a stone's throw inclusions of similar rock may have been enveloped by the same magma with no apparent sign of fusion. These latter inclusions were doubtless enveloped by the magma when its temperature was too low to bring about fusion.

In the Adirondacks, assimilation products appear to have been produced in at least three ways: (1) By the so-called "lit-par-lit" and

"mosaic" types of injection as described by Cushing; (2) by simple melting and absorption of borders of small and large inclusions, and (3) by engulfment and partial to complete assimilation of Grenville fragments or inclusions.

ORIGINAL BANDED STRUCTURES IN THE SYENITE AND GRANITE

Features of special interest in connection with the granites and syenites, especially the former, are the frequent and comparatively sudden transitions from the gray to the pink varieties and from the more syenitic or basic phases to the more truly granitic phases. The effect is to give wide bands or layers, from 1 or 2 to 100 or more feet wide, of varying color and composition, and yet all clearly belonging to the same rock mass because of the true, though often pretty rapid, gradation of one band or layer into another. These bands always appear to be arranged parallel to the foliation. Many examples of such phenomena have been observed by the writer.

Cushing and Kemp have described such banded rocks in the Long Lake³⁴ and Elizabethtown-Port Henry³⁵ quadrangles, respectively, and they are inclined to regard the banding as due to differentiation of the magma into layers of varying composition. For many cases, at least, the writer agrees with this view, though in certain other cases, however, he believes the banded structures have been produced by more or less thorough fusion, but only partial assimilation of long, narrow Grenville gneiss inclusions. Detailed records of observations in support of this view are being accumulated, and the results will be presented in a later paper.

³⁴ H. P. Cushing: N. Y. State Mus. Bull. 115, 1907, p. 478.

³⁵ J. F. Kemp: N. Y. State Mus. Bull. 138, 1910, pp. 48 and 128.



FLAT SHARP-EDGED PEBBLES FROM THE GALENA FORMATION

CHARACTERISTICS OF A CORROSION CONGLOMERATE¹

BY FREDERICK W. SARDESON

(Read before the Society December 30, 1913)

CONTENTS

	Page
Introduction.....	265
General discussion.....	265
Formational relations.....	268
Corrosion surfaces.....	268
Corrosion conglomerate.....	269
Conglomerate in the Galena formation.....	269
General description.....	269
Origin of limestone pieces in the shale.....	270
Condition of the shale on the sea-bottom.....	271
Fucoids.....	271
The work of sea-weeds.....	272
Characteristics of corrosion conglomerate.....	273
General characteristics.....	273
Composition of pebbles.....	273
Color.....	273
Surface of pebbles.....	274
Amount and distribution.....	274
Preservation.....	275
Conclusion.....	275

INTRODUCTION

GENERAL DISCUSSION

The conglomerates of the Galena-Trenton series of the Ordovician have been once before described² in an article in the *American Geologist*. At that time those conglomerates were interpreted as intraformational in contradistinction to basal or interformational conglomerate.³ They were

¹ Manuscript received by the Secretary of the Society December 31, 1913.

² F. W. Sardeson: Intraformational conglomerates of the Galena series. *The American Geologist*, vol. 22, 1898, p. 315.

³ Charles D. Walcott: Paleozoic intraformational conglomerate. *Bull. Geol. Soc. Am.*, vol. 5, 1894, p. 191.

interpreted as corrosional in contrast with such as are commonly formed by erosion. It is my purpose now to describe one of those conglomerates in particular and to discuss its significance in relation to other conglomerates. The conglomerate to be described here is a thin or scattering deposit in the form of black-surfaced pebbles of limestone (see plate 12) in a greenish shaly limestone matrix. It occurs above the base of the Galena limestone formation proper. It is best known at Saint Paul, Minnesota, but is seen also at Kenyon, near Mantorville, and in other places where the base of the Galena is exposed.

The mere occurrence of conglomerate in this region is not exceptional. There are many conglomerate beds in the Upper Cambrian and the Ordovician in the territory near Saint Croix and Mississippi rivers, in Minnesota and Wisconsin. Nearly all, if not all, of the several formations comprised in the Cambrian and Ordovician here have some conglomerate in them. The conglomeratic beds are, as a rule, thin deposits and, if taken all together, they would not be very great in amount. They correspond in that respect with the rather thin, very widely extended rock formations in which they lie. They are all noteworthy as geologic evidence, even though they are thin or inconspicuous. The bed of conglomerate here in the Galena limestone formation is even thinner or more scattered than many others. On the other hand, its pebbles are remarkably well preserved and very favorable for study.

That which is considered to be most noteworthy about this particular conglomerate is that it appears to be the result of corrosion, or at least not of the ordinary processes of erosion. Obviously, a widely different conclusion results from the interpretation of a particular conglomerate bed as a marine corrosional product, as compared to that which follows if it is interpreted as a basal erosional conglomerate. Whether the sea made this conglomerate while relatively quiescent, or whether the sea withdrew some hundred miles southward and returned again, leaving as record of its changes these blackened cake-shaped pebbles, is the question involved in case of the conglomerate here described.

In regard to the interpretation of all conglomerates in this region, they all lie in or adjacent to formations that bear marine fossils, and where evidence to the contrary is not in preponderance they may, therefore, all be forthwith interpreted according to prevailing theories at the present time, as evidence that the sea had been repeatedly withdrawn from the region and again returned to it. I may say here that I think several of them may have been produced in such recession and readvance of the sea, but that some others were not, and of these in particular the

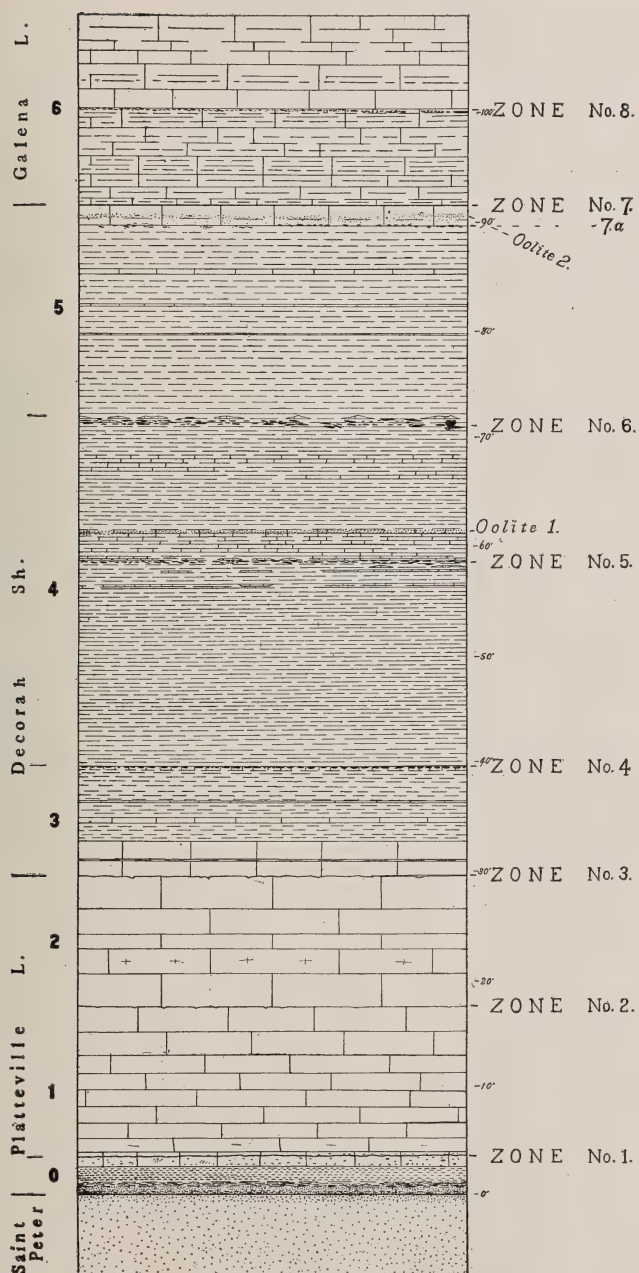


FIGURE 1.—Section at Saint Paul, Minnesota

Showing the position of corrosion surfaces and conglomerates

one here described. There is in fact a variety of conglomeratic deposits comprised in the Cambrian and Ordovician in this region. Sea-beach pebbles, probably also river gravel, certainly some lag-gravel, with "dreikanter," and some marine corrosion pebbles, besides reef breccia, or conglomerate, characterize different ones of the known conglomerate beds, and they show that there was a diversity of conditions under which conglomerates were formed. Several of the conglomerate beds appear to be problematic, and they may be considered more especially at some future time. With them are placed for the present certain false conglomerates.

FORMATIONAL RELATIONS

A brief outline description of the corrosion phenomena and the reason for calling the deposits intraformational corrosion conglomerate may be given again here. At Saint Paul, Minnesota, there are eight zones at which evidence of corrosion is found in a vertical section of about 110 feet. Of the eight zones two (numbers 2 and 3, figure 1) are merely blackened corroded top faces of limestone strata. Two others (numbers 1 and 7) are corrosion surfaces, with associated black pebbles, while the rest (numbers 4, 5, 6, and 8), including the one especially considered here (number 8), are conglomeratic only. The eight zones are in the several distinguishable beds or faunal zones of the Galena-Trenton series next above the Saint Peter sandstone. As properly named, the Platteville limestone includes beds numbers 1 and 2, the Decorah shale includes beds numbers 3, 4, and 5, and the base of the Galena limestone, which is rather shaly here also, is bed number 6. Thus the corrosion zones 1, 2, 4, 5, 6, and 8 are intraformational, and numbers 3 and 7 are pactly so, too, since the formational distinction is mainly technical. Further, the zones numbers 2, 3, and 7 can be nothing other than the result of corrosion, as shown by their features, which are as follows:

CORROSION SURFACES

The faces of certain limestone strata are uniformly blackened by a stain which penetrates with a diminishing intensity an inch or so downward into the fresh limestone. The black-stained surfaces lie, as a rule, along seams between strata, but belong distinctly to the top of the subjacent stratum and never to the bottom of the superjacent one. Where the black surface or seam cuts through fossils, as frequently occurs, there are remaining parts of them in the limestone below the seam, but none above it, just as must be the case where the top of a limestone had been corroded or eroded before the succeeding stratum was deposited. There is in fact an unconformity on a small scale at each corrosion surface,

which is quite noticeable in freshly quarried rock, because the limestone or shales that cover them are not discolored and yet penetrate holes and cavities of the corroded surfaces. The particular reasons for interpreting these as marine corrosion surfaces are because the caverns and burrows extending down into the blackened limestone are filled with fresh marine sediment and not with terrestrial residuum. The black coating of iron and manganese is unlike that of weathered surfaces excepting perhaps those of the deserts. The blackened surfaces are found to be encrusted occasionally by marine fossil animals, and some of the encrusting fossils are in turn corroded. The manner in which the black surfaces originated is believed to be simply this: that the deposition of terrigenous material, chiefly clay, ceased for a time, and the lime deposit was meanwhile dissolved away by the sea-water as fast or faster than it was contributed by sea-weeds, shells, and the like. The black surface deposit of iron is a sort of residuum.

CORROSION CONGLOMERATE

In the conglomerates the pebbles have the same general surface characteristics as those of the described corrosion surfaces. In the lowest corrosion zone (number 1, figure 1) these are in fact small, blackened, irregularly shaped pebbles associated with the corrosion surface, so that their origin as loosened, corroded fragments is not far to seek. The other conglomerates in zones numbers 4, 5, 6 and 8 (figure 1) are not directly associated with the blackened surface of a corroded limestone stratum. Their pebbles are in fact isolated in matrix of clay-shale or of shaly limestone. The pebbles themselves are, however, limestone, with blackened surfaces, the black stain penetrating with diminished intensity into them, as in the case of the corrosion surfaces of limestone strata described. In the corrosion zones numbers 5, 6, and 8 (figure 1) the pebbles are large. They are mostly a few inches wide, but range in size from that of coarse sand to pieces a foot wide. They are in fact too coarse to be explained as incidental fragments from a corroded limestone surface, even if they were directly associated with such a surface. Further explanation is needed, therefore, to account for them. It will be sufficient to explain one of these conglomerate beds, since the others are essentially like it.

CONGLOMERATE IN THE GALENA FORMATION

GENERAL DESCRIPTION

Taking the conglomerate of the base of the Galena—zone number 8, figure 1, as the best example—the matrix of this bed (number 6) is

bluish gray in color, so that the corrosion pebbles, which are black, appear in strong contrast. The matrix is shale and shaly limestone, with some thin strata of compact limestone. It contains also many lenticular limestone laminae and many nodular or irregular pieces of limestone besides the conglomeratic pebbles. Those lenticular and irregular limestones in the shaly matrix appear to be the kind of materials out of which the blackened pebbles were made. The limestone pieces have the bluish color of the shaly matrix, and thus are different from the conglomeratic pebbles in not being black. They are distributed in zones throughout the bed vertically, while the conglomerate is in a limited zone. Those bluish limestone pieces are not at all encrusted by marine fossils, while the conglomeratic pebbles often are. In shape these bluish limestones and the black pebbles are, however, much alike; both comprise also the same diversity of texture, and they contain the same species of fossils. That the conglomeratic pebbles are merely corroded and blackened limestone pieces, such as those still abundant in the shales of this bed, is further evident from the fact that a few flat pieces of limestone, 2 or 3 feet wide, have been discovered to have their upper side blackened and corroded like those of the pebbles, while their lower side is that common to mere limestone pieces—that is, they are half-made pebbles. The pebbles contain fossils—*Receptaculites oweni* Hall, *Clitambonites diversa* Shaler, and others—some of which occur only in this bed number 6, so that the conglomerate could not have come from the disruption of an older bed. Finally, there is no noticeable change of fauna between the strata below and above the conglomerate. It is strictly intraformational.

In considering the conditions under which this conglomerate was formed, (1) the origin of the limestone lenses and nodules in the shales, and (2) the force that turned some of them over as pebbles to be corroded on both sides need to be explained.

ORIGIN OF THE LIMESTONE PIECES IN THE SHALES

The nodules and lenticular layers of limestone in the shales of bed number 6 are the direct result of deposition of lumps and cakes of lime on the sea-bottom. The entire Galena-Trenton series has such deposits, and evidence of their origin can be seen in other parts of it, as well as in bed number 6. For example, limestone bed number 1 is made up partly of shaly seams, but mainly of irregular patches of more and less calcareous material.⁴ This structure is the pseudobrecciation as described by R. C. Wallace in the same limestone formations of the Ordovician in

⁴For chemical analyses of these, see C. W. Hall: Bull. Minn. Acad. Nat. Sciences, vol. 3, p. 120. 1889.

Manitoba.⁵ Where there is a predominance of shale, that material takes the place of the less calcareous part of the rock, while the more calcareous part lies in more or less abundance in layers, lenses, and nodular patches within the shale. In the base of bed number 3 lumps, cakes, and lenses of pure light-colored, fine-grained limestone lie isolated in a brown fucoidal shale, and the evidence is there very clear that the lime was originally deposited in lumps or masses. The lime quite certainly came mainly from the decomposition of marine algæ in the manner lately described by Thomas C. Brown.⁶ Without entering into a discussion of the question as to what plants and animals may have contributed to the lime deposit, or in what manner the lime was collected, it is sufficiently evident to me that something deposited lime in small and large masses. The lenses and lumpy patches of relatively pure lime in all parts of the Galena-Trenton frequently inclose fossil shells, etcetera, in a way to show that these lime bodies were soft when deposited—that is to say, they often partly inclose shells, stipes of graptolites, fucoids, etcetera, either in the manner of objects overflowed by soft lime or in the manner of objects partly sunken into such a soft deposit. Shells of *Lingula* are found which had bored into them, and the boring was, of course, done while they were not yet consolidated. In case of the bed number 6, the strata consist partly of clay-shale that was deposited particle by particle and partly of the limestone lenses and pieces that appear to have been deposited in small masses.

CONDITION OF THE SHALE ON THE SEA-BOTTOM

On the floor of the sea all appears to have been hard or solidified excepting the newest mud and new lumps of lime on its surface. There is at least no good evidence that the sea-floor was muddy. Even the fossil bivalves, the Pelecypoda are not of the kind here that necessarily burrowed in mud, but all are referable to either *Anisomyaria*—such as live anchored, or to *Taxodonta*—such as could presumably flatten the foot and crawl on firm surfaces as the living *Nucula* is said to do. The Brachiopod *Lingula* occurs also, as said, chiefly in the limey lumps, into which it could burrow while those were fresh, not yet consolidated.

FUCOIDS

An apparent objection to the view that the sea-floor was hard should be explained here. There are many fossils, such as might be at present

⁵ R. C. Wallace: Pseudobrecciation in Ordovician limestone in Manitoba. The Journal of Geology, vol. 21, 1913, p. 402.

⁶ Thomas C. Brown: The origin of certain Paleozoic sediments. The Journal of Geology, vol. 21, 1913, p. 232.

most acceptably spoken of as worm-burrows, but which are more familiarly called "fucoids." An abundant species of them here has been named and referred by E. O. Ulrich to the fossil sponges.⁷ These fossils are twig-shaped, from 5 to 10 millimeters wide, more or less branched, and are bluntly rounded at the ends. Their surfaces have organic symmetry, but internally they are filled with heterogeneous concentrate of shell fragments, or whatever kind of coarse grains the surrounding matrix contains. These "fucoids" lie horizontally in the shales, but often bend conformably to the surfaces of shells or pebbles. I think they were most probably the root-like hold-fasts of sea-weeds, the hollows or interiors of which were later used by robber-worms as holes or burrows. The hold-fasts were, of course, attached to the sea-floor, and in many cases, if not as a rule, they were buried under partially consolidated sediment before being inhabited and consequently filled with the refuse plunder of robber-worms. They are even frequently associated with undoubted fucoidal imprints that have the same size and profile as the *Camarocladia*, but are flat. Those may belong to the same organic species, but were not filled out with sand or other coarse debris. There are also "fucoids" besides *Camarocladia rugosa*. The *Licrophycus otta-waense* Bill., occurs in the bed (number 6) here and might be interpreted as worm-burrows. None of these "fucoids" nor any worm-burrows penetrate the shales as if the sea-bottom had had more than a thin covering of unconsolidated mud at any time.

THE WORK OF SEA-WEEDS

The corrosion of lenses and nodules of limestone into conglomerate may be explained as the consequence of slow deposition of sediment and the action of sea-weeds in pulling up the sea-bottom. The corrosion of the exposed surface of limestones has already been explained. To account for flat conglomeratic pebbles of limestone which are corroded on both sides, they must further be supposed to have been turned over by some force. Flat pebbles, a foot wide, would require a considerable force to turn them over. The force might have come through sea-weeds. The "fucoids," already described in the preceding paragraph, indicate the existence of large kelp-like sea-weeds, which when anchored to calcareous lumps on the sea-bottom and drawn by sea current might readily drag them or turn them over. Whatever the force that turned the flat pebbles over, it also occasionally left one as now found standing edgewise.

The reason for ascribing this conglomerate to the disturbance by sea-

⁷ *Camarocladia rugosa* Ulr.: Final report Geological and Natural History Survey of Minnesota, vol. 3, part 2, 1897, p. xcv.

weeds rather than to the usual force of waves is frankly admitted here to be because it appears impossible for waves to have made such pebbles. The amount of waste or wear of the pebbles was great. It has reduced them to a half or a tenth of the bulk of the original limestone pieces, yet it has not reduced them to uniform size or shape. The pebbles have, of course, a flattened and smoothed appearance, but the raised or jutting parts of them are not more worn than are hollows and depressions of the surfaces. Their edges are not regularly rounded, as is the case with well-worn beach pebbles, but rather their edges are sharp and thin and often jagged.

CHARACTERISTICS OF CORROSION CONGLOMERATE

GENERAL CHARACTERISTICS

The characteristics of marine corrosion conglomerate—the features by which such deposit is to be recognized—can perhaps not be fully determined from its occurrence in one place. The features of the conglomerate here described are, briefly, the following: The pebbles are limestone in either shale or shaly limestone as matrix. They have a black and more or less smoothed surface. Their surface is rounded convex and concave or pitted and jagged. They are often flat and sharp edged, but retain more or less of the original shape of the limestone lenses and nodules from which they derived. The fossil contents in the pebbles are the same as those that characterize the strata in which they lie.

COMPOSITION OF PEBBLES

In case of other conglomerates which like this one formed at some distance from the shore, some, if not all, of the same features should be found on them and may be recognized. Such a conglomerate, for example, should contain limestone. A relatively soluble rock, such as a limestone, is the only one which when broken on the sea-floor would be corroded readily so as to form conglomerate. A sandstone with lime cementing material might, of course, be made into pebbles, and the insoluble concretions, chert, etcetera, from a disrupted limestone might also mingle with pebbles of limestone; but those materials other than limestone might seldom, if ever, be perceptibly corroded or blackened.

COLOR

The black stain, together with smoothed corroded surface, is a marked characteristic in the conglomerate here described, but in other cases the black stain might be inconspicuous—for example, where the matrix is

also black or where the stain has been altered or weathered. The black may be changed to the yellow color of limonite. Associated with the corrosion conglomerates in the Galena-Trenton series at Saint Paul, Minnesota, there are two zones of yellow oolitic limonite (see figure 1). The largest grains of the limonite have the form of corrosion pebbles. Grains of this limonite are found that are an inch wide and one-fourth of an inch thick and are shaped, as said, like corrosion pebbles, while small grains are round, oolitic. This limonite-oolite is a form of corrosion conglomerate, or, as it appears to me, it is a black corrosion's product changed by the addition of ferruginous deposition. If this limonite is considered as a corrosion conglomerate, then black color appears a less dependable characteristic than is the form of the pebbles; also weathering or leaching of the black coating on the pebbles of zone number 8, here described, changes it to rusty brown. In such cases the pebbles look very much like ferruginous concretions when seen broken in a solid matrix, or when they are weathered free from a shaly matrix and their color has faded they can be recognized only by their shape.

SURFACE OF PEBBLES

Pitted or jagged surface features would presumably not appear on corroded pebbles if the limestones of which the pebbles consist were very uniform in texture and composition; but if the original surfaces of such limestone pieces were concave or angular they might remain more or less concave and angular, just as the original form of lenses and lumps is reflected still in the conglomerate here described. If, for example, the sea-floor should be brecciated by the shock of earthquakes, either alone or combined with the drag of sea-weeds, such breccia might remain comparatively rhombic even when well corroded. In other words, corrosion conglomerate may be expected to bear close resemblance to breccia in some cases as it does to concretionary structure in others, such as in the one here described.

AMOUNT AND DISTRIBUTION

In amount of deposit corrosion conglomerate may be expected to be rather thin, widely scattered, as in this case. Its distribution may also be irregular. The black pebbles of the Galena at Saint Paul, Minnesota, sometimes lie in small heaps, as if thrown together, and again they are very thinly scattered. They recur for 80 miles. A few stand on edge. Not enough stand edgewise in this case to make an "edgewise conglomerate."

erate,"⁸ but the possible relation or confusion locally with edgewise conglomerate may be at least mentioned here.

PRESERVATION

The conglomerate in the Galena is finely preserved. This is evident from association of many perfect fossils, as well as from the pebbles themselves. Fine preservation can, of course, not be claimed as a characteristic of conglomerates of any kind. If they occur in undisturbed shaly matrix or associated with many well kept fossils, the condition of the pebbles should at least be good. But the probability that corrosion conglomerates often lie in porous limestone or sandstone where they can be leached and more or less defaced must be considered in addition to the probability, as indicated in the preceding paragraphs, that conglomerate formed at least in essentially the same way as these may originally bear little that is characteristic. Any limestone conglomerate, therefore, that does not contain pebbles which are characteristic of lag-gravel, river, sea-beach, or other gravel may be suspected of being corrosion conglomerate. I may add here that the name corrosion conglomerate is used by me not because no mechanical agent is involved in forming them, but merely because corrosion surface would be the most persisting feature when once developed.

CONCLUSION

As interpreted, the occurrence of conglomerate in the Galena is in itself not of great significance. It represents merely a time of quiet or failure of sedimentary deposition. Times of no deposition were probably common enough while formations of the Cambrian and Ordovician were making—that is why they are thin—in this region. Some of those times are represented by intraformational conglomerates and some are not, if conditions of the Galena-Trenton are typical. Greater significance arises from the example or evidence which the study of this conglomerate affords, tending to show that conglomerate can be formed in the sea under diverse conditions; that not all marine conglomerate is made on the shores.

In conclusion, an estimate is attempted with respect to the agents and to the probable limit of the conditions under which corrosion conglomerate might have formed. Two probable agents—giant sea-weeds and earthquakes—have already been mentioned. Giant sea-weeds anchored to the bottom, if entangled by rafts of other sea-weeds driven by

⁸ G. W. Stose: Folio 170, U. S. Geological Survey.

storms or by sea-currents—a sort of sargasso—would appear to be a sufficiently powerful agent to tear up the bed of shallow sea, at least under favorable conditions, over very wide areas. Earthquakes might be the direct cause of loosened stone on the sea-bottom; or, again, of currents such as to cause dragging up of the bottom by sea-weeds. C. D. Walcott⁹ mentions ice as a possible cause of Paleozoic intraformational conglomerate. Folding or faulting of the sea-bed, as it appears to me, might raise and expose an area to sea-current and thus prevent deposition for a time, and allow corrosion conglomerate to form, without the sea-bottom anywhere rising above sealevel. Since the conglomerates are found in limited horizons instead of throughout the beds or formations, their origin is to be attributed rather to catastrophies such as rafts of sea-weeds, etcetera, than to mere exposure of the sea-bottom by cessation of sedimentary deposit or to other general cause. The agents and circumstances just mentioned would further indicate shallow sea as the place where corrosion conglomerate formed. Its place of origin lies, therefore, more or less closely to the seashore or to where beach gravels might be forming. The significance of shore-erosion conglomerate and of corrosion conglomerate in regard to the place or depth of sea indicated by the one or the other is not widely different. There is a much greater difference with respect to permanence of the sea. If intraformational or other conglomerate that extends 50 or 100 miles wide is interpreted as erosional, it means that the sea once retreated and, of course, readvanced its shore across that entire area; while if the conglomerate is interpreted as corrosional, it means a quiescent period, at least as to retreat and readvance of the sea.

⁹ Loc. cit.

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CONTENTS

	Pages
Medina and Cataract Formations of the Siluric of New York and Ontario. By Charles Schuchert - - - - -	277-320
Close of the Cretaceous and Opening of Eocene Time in North America. By Henry Fairfield Osborn - - - - -	321-324
Cretaceous-Tertiary Boundary in the Rocky Mountain Region. By F. H. Knowlton - - - - -	325-340
Boundary Between Cretaceous and Tertiary in North America as Indicated by Stratigraphy and Invertebrate Faunas. By Timothy W. Stanton - - - - -	341-354
Cretaceous-Eocene Correlation in New Mexico, Wyoming, Montana, Alberta. By Barnum Brown - - - - -	355-380
Evidence of the Paleocene Vertebrate Fauna on the Cretaceous-Tertiary Problem. By W. D. Matthew - - - - -	381-402
Recent Results in the Phylogeny of the Titanotheres. By Henry Fairfield Osborn - - - - -	403-405
New Methods of Restoring Eotitanops and Brontotherium. By Henry Fairfield Osborn - - - - -	406
Restoration of the World Series of Elephants and Mastodons. By Henry Fairfield Osborn - - - - -	407-410
Rectigradations and Allometrons in Relation to the Conceptions of the "Mutations of Waagen," of Species, Genera, and Phyla. By Henry Fairfield Osborn - - - - -	411-416
Geology of the Uinta Formation. By Earl Douglass - - - - -	417-420
Cambrian and Related Ordovician Brachiopoda—a Study of Their Inclosing Sediments. By Lancaster D. Burling - - - - -	421-434

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MEDINA AND CATARACT FORMATIONS OF THE SILURIC OF NEW YORK AND ONTARIO ¹

(Presented in abstract before the Society December 30, 1912)

BY CHARLES SCHUCHERT

CONTENTS

	Page
Introduction.....	278
Part I.....	278
The Cataract formation.....	278
General discussion of the formation.....	278
Upper Cataract or Cabots Head shale member.....	280
Middle Cataract or Manitoulin limestone member.....	280
Basal Cataract or Whirlpool sandstone.....	281
The Cataract fauna.....	281
The Medina formation.....	285
The Medina fauna.....	288
Relations of the Cataract to other Siluric faunas.....	290
Species of the Cataract fauna.....	290
Relation to the Medina.....	290
Relation to the Brassfield.....	291
Relation to the Siluric of Anticosti.....	292
Contacts between the Medina, Cataract, and Clinton.....	292
Summary of sections 340 miles apart.....	296
Part II.....	297
History of the Medina formation.....	297
Amos Eaton.....	297
T. A. Conrad.....	298
James Hall.....	299
C. A. Hartnagel.....	302
A. W. Grabau.....	302
Lardner Vanuxem.....	303
The Siluric sections in detail from Rochester, New York, to the head of Lake Huron.....	304
Rochester, New York, section.....	304
Medina, New York, section.....	306
Lockport, New York, section.....	307
Niagara Gorge, New York-Ontario, section.....	308

¹ Manuscript received by the Secretary of the Geological Society March 17, 1914.

	Page
Thorold, Ontario, section.....	310
Grimsby, Ontario, section.....	310
Stony Creek, Ontario, section.....	311
Hamilton, Ontario, section.....	313
Dundas, Ontario, section.....	315
Limehouse, Ontario, section.....	316
Glenwilliam, Ontario, section.....	317
Cataract, Ontario, section.....	317
Collingwood, Ontario, section.....	318
Owen Sound, Ontario, section.....	319
Cabots Head, Bruce Peninsula, Ontario, section.....	319
Manitowaning, Manitoulin Island, Ontario, section.....	320

INTRODUCTION

This contribution to stratigraphy redefines the Medina formation and describes the character of its strata and fauna in the typical area in the State of New York. The new Cataract formation of Ontario is also described in detail and its fauna listed. Some of the most characteristic species of the latter formation were formerly ascribed to the Clinton, but it is here shown that the Cataract is equivalent to the Medina—the typical Medina as seen at Medina, New York. Finally, these two formations are compared with the Brassfield of Ohio, which has also been correlated with the Clinton, but is now seen to be of about the same geologic time as the Cataract and the Medina.

The following account of the Cataract, Medina, and Brassfield is divided into two parts. Part I contains a general discussion of the formations, their faunas, and their interrelations. In the second part is given a historical review of the Medina and the status of the various formation names, followed by a detailed description of sixteen sections extending from Rochester, New York, to the Manitoulin Islands, a distance of 340 miles, and taken at the places in which the Medina and Cataract formations are best exposed. Hence the detailed evidence for the nomenclature and stratigraphy discussed in Part I will be found in Part II.

PART I

THE CATARACT FORMATION

General discussion of the formation.—The writer became acquainted with this formation at Hamilton and Grimsby, Ontario, in September, 1895, under the guidance of that grand old naturalist, Col. Charles Coote Grant. The formation was then known as the Clinton formation, due

to an error made by Hall previous to 1852² and perpetuated by every geologist since working in Ontario. Even though at that time the writer collected *Dædalus archimedes* and *Arthropycus alleghaniense* at Grimsby in this so-called Clinton, he noted that these fossils had two occurrences—one in Medina, the other in the Clinton of Ontario; but it was not until the summer of 1912, while geologizing in the Georgian Bay region of Ontario with Dr. Merton Y. Williams, of the Geological Survey of Canada, that the error became apparent. Here in the northwest limestones predominate, and these had also been regarded as of Clinton age; but there is here an abundance of *Cælospira planoconvexa*, *Rhinopora verrucosa*, and *Helopora fragilis*, forms of the "Clinton" of Hamilton, with none of the guides characterizing the Clinton fauna as developed between Niagara Falls and Rochester. The former fauna rested either on the abundantly fossiliferous Richmond or on the Queenston red shales. This superposition at once raised the question, What has become of the Medina?

Later in the same season, while in the Georgian Bay-Manitoulin country, the writer was so fortunate as to meet in the field Prof. William A. Parks, and to him our difficulties were related. Together we decided to restudy the sections at Hamilton and Grimsby, and from such a study it soon became plain that the Ontario "Clinton" not only underlay a vanishing remnant of the true Clinton with *Pentamerus oblongus*, but, what surprised us more, the fossiliferous Medina was also above these beds, though greatly thinned. Professor Parks then told the writer of the well exposed section at the cataract of the Credit River, where there is not a trace of the Medina, and after two days spent here it was decided to make this the typical section for the new Cataract formation. The writer, however, then held that the Cataract underlay the Medina, and that these formations were not the equivalents of each other. These occurrences were announced before the Paleontological Society at its New Haven meeting, in December, 1912, and the results and the name *Cataract formation* were later accepted in Guide Book Number 5, prepared by Parks for the Twelfth International Geological Congress and issued by the Geological Survey of Canada in 1913.

The Cataract formation is typically developed along the forks of the Credit River, and is especially well exposed at the cataract, as has been said. Here the formation has a thickness of about 106 feet. This is the average development, though in the various sections the formation varies between 54 feet (Niagara) and 126 feet (Manitoulin). To the south-east, toward Niagara River, the formation becomes more muddy and

²Pal. N. Y., vol. II, 1852.

sandy, while toward the northwest the sands at the bottom vanish first, the middle portion becomes increasingly more limestone, and the upper shales become more and more red and unfossiliferous toward the Manitoulin. In Ontario, where the formation is typically developed, it is readily divisible on its petrologic and faunal character into three members, as follows:

Upper Cataract or Cabots Head shale member.—This was first named Kagawong by Williams;³ but as this name had been used by Foerste for an Ordovician formation, Williams now proposes to use the term Cabots Head, as given by Grabau.⁴ The member consists of a series of shales, usually greenish in color and somewhat calcareous, with occasional thin beds of magnesian limestone; toward the northwest the top of this member becomes more and more red or locally ferruginous, and finally is completely transformed into soft, red, almost unfossiliferous shales, which are in color much like Queenston, though less sandy. The thickness is variable, between 20 feet (due to erosion of the top before being covered by the Lockport) and 75 feet (where the shales are thickest the limestones below are thinnest).

These shales are locally rich in bryozoans, and particularly in the ferruginous zones near the top of the member, where there is also more or less of magnesian lime material. Here *Helopora fragilis*, *Pachydictya crassa*, *Phanopora explanata*, *P. ensiformis*, *Callopora magnopora*, and *Trepotomata* Bryozoa abound, especially at Limehouse and Dundas. Other fossils, except *Lingula clintoni* (*oblonga* of local collectors) and *Pterinea* ? *primigenia*, are very scarce. Wherever a thin limestone is present it is usually seen to be made up of one or two species of *Helopora*.

Middle Cataract or Manitoulin limestone member (Williams, 1913).⁵—Strata variable in character from heavy-bedded, somewhat magnesian limestones, with local reefs of corals and bryozoans, to thinner bedded, highly magnesian, and more or less impure limestones. Locally in the south there are even thin beds of sandstone. The thickness varies between 60 feet in the north and 9 feet (Dundas), or even nothing in the south (Niagara). In other words, the limestones are translated more and more into shale southeastward.

This division is nearly always rich in fossils and is the home of most of the Cataract forms other than the bryozoans, though many of these are also to be had here. The guide fossils are *Clathrodictyon vesiculosum*, *Acervularia* (?) *gracilis*, *Diphyphyllum vennori*, *Rhinopora verru-*

³ Ottawa Nat., vol. 27, 1913, p. 37.

⁴ Bull. Geol. Soc. Am., vol. 24, 1913, p. 460.

⁵ Op. cit., p. 38.

cosa, *Phylloporina angulata*, *Hebertella fausta*, *Atrypa* n. sp. (a multi-striate and large form of *A. marginalis* type), and *Cælospira planoconvexa*.

Basal Cataract or Whirlpool sandstone (Grabau).⁶—This coarse, cross-bedded, white, red, or mottled sandstone occurs at the base of the Cataract all the way from Lockport, New York, to near Collingwood, Ontario, a distance along the outcrops of about 150 miles. The thickness varies between 22 feet and 6 feet, with the maximum in the southeast. Farther northwest the limestones make the base of the Cataract formation, and therefore one of these two basal members rests with sharp distinction and discordance on either the Queenston or Richmondian of the Ordovician.

The Whirlpool is practically barren of fossils, though at the very top a few forms may be had, chiefly worm burrows and more rarely *Modiolopsis* (?) *orthonota*.

THE CATARACT FAUNA

Hall⁷ described from or identified at Flamborough Head, near Dundas, 9 species, all erroneously determined as from the Clinton. Logan and Billings⁸ list a larger number of forms, also from the "Clinton," all of which are in the Cataract formation. Nicholson⁹ has a list of 29 species that are also said to be from the Clinton, but in reality are from the Cataract, and Parks¹⁰ lists at least 31 forms. A part of Grabau's¹¹ Medina fauna likewise belongs here.

The following list combines all previous lists, contains those additional species identified by the writer, and eliminates the forms now known not to occur in this fauna. The symbols used are as follows: * = restricted to Cataract, × = of no stratigraphic value, + = also in higher formations, ++ = affinity upward, m = also in Medina, and b = also in Brassfield.

FUCOIDS:

× *Bythotrephes gracilis intermedia* and *B. gracilis crassa* Hall. Common at various horizons in the two upper members. Identified by Nicholson.

BURROWS:

m × *Scolithus verticalis* Hall. Dundas and elsewhere in the Whirlpool. At Stony Creek, in the Medina. Originally described from the Medina of New York.

⁶ Jour. Geol., vol. 17, 1909, p. 238.

⁷ Pal. N. Y., vol. ii, 1852, pp. 41-51.

⁸ Geol. Canada, 1863, pp. 313-321.

⁹ Rept. Pal. Prov. Ontario, pt. 2, 1875, pp. 40-49.

¹⁰ Guide Book No. 5, Inter. Geol. Congr., 1913, pp. 10-12.

¹¹ Loc. cit.

×*Arenicolites sparsus* Salter. These are paired holes seen in many formations; therefore of no stratigraphic and but little biologic value. Nicholson identifies this European species at Dundas.

×*Planolites vulgaris* Nicholson. Originals from Dundas.

HYDROIDEA:

b+*Clathrodictyon vesiculosum* Nicholson. Rare in Manitoulin member. (See Parks, Univ. Toronto Studies, Geol. Ser., 5, 1908, p. 14.)

×*Retiolites venosus* Spencer, not Hall. The writer can not make out what Spencer figures, but it is certain that he has no graptolite and certainly not the characteristic form of the Clinton.

×*Dictyonema*. At least two species occur in the Manitoulin member at Forks of Credit River.

CORALS:

+*Zaphrentis bilateralis* (Hall). Originally described from the Clinton and higher beds. Common in Manitoulin member.

+*Halysites microporus* (Whitfield). Always rare. In Manitoulin member at Manitowaning and elsewhere.

+*Heliolites interstinctus* (Linnæus). Rare in southern localities, but common in Manitoulin member at Manitowaning.

b+*Diphyphyllum cæspitosum* (Hall)? Manitoulin member, Manitowaning.

**Diphyphyllum vennori* (Billings). Originals from the Manitoulin member at Manitowaning. A good species.

b**Acercularia* (?) *gracilis* (Billings). Originals from Manitowaning, where it is common (*Strombodes gracilis*). Manitoulin member. In the Brassfield of Ohio is the related *A.* (?) *clintonensis* Nicholson.

b+*Favosites venustus* (Hall). Common in Manitoulin member at Manitowaning.

STARFISHES:

**Mesopalæaster granti* (Spencer). Originals from the Cabots Head member at Hamilton.

**Mesopalæaster* (?) *cataractensis* Schuchert. Originals from the Cabots Head member at Hamilton.

TUBICULOUS ANNELIDA:

b**Cornulites distans* (Hall). Originally described from the "Niagara group" at Flamborough Head, but is from the Manitoulin member of the Cataract. Nicholson also notes it from Dundas.

**Cornulites neglectus* (Nicholson and Hinde). Originals from Dundas. Probably Manitoulin member.

ERRANT ANNELIDA:

*At Dundas, Hinde got and described from the Cataract the following teeth: *Eunicites clintonensis*, *E. coronatus*, *E. chiromorphus*, *Enonites amplus*, *Æ. fragilis*, *Arabellites elegans*, *Lumbriconerites basalis*, *L. triangularis*, *L. armatus*, and *Glycerites calceolus*.

BRYOZOA:

+*Helopora fragilis* Hall. Originally described from the Clinton of New York and the "Clinton" of Flamborough Head, Ontario. Distributed throughout the two upper members of the Cataract.

- d**Rhinopora verrucosa* Hall (syn. *R. venosa* Spencer). Originals from Flamborough Head. Widely distributed throughout the Manitoulin and lower Cabots Head member, and one of the guides.
- **Phænopora explanata* Hall. Originals from Flamborough Head, in Cabots Head member.
- +*Phænopora constellata* Hall. This Clinton species is identified by Nickles and Bassler at Hamilton.
- b**Phænopora ensiformis* Hall. Originals from Flamborough Head, in Cabots Head member.
- **Phænopora punctata* (Nicholson and Hinde). Originals from Dundas as *Ptilodictya punctata*; probably lower Cabots Head member.
- b+*Pachydictya crassa* (Hall). Originals from the Clinton of New York as *Stictopora crassa*; also identified at Flamborough Head. Cabots Head and Manitoulin members.
- Nematopora raripora* (Hall). Originals from Flamborough Head as *Stictopora raripora*; probably from lower Cabots Head member; also in Rochester of New York.
- b+*Phylloporina angulata* (Hall). Originals from the Clinton of New York as *Retepora angulata*. Not rare in Manitoulin member.
- ×*Fenestella bicornis* Spencer. Originals from Hamilton. Species not as yet recognizable.
- +*Fenestella tenuis* Hall. This Clinton form Nicholson identifies doubtfully at Dundas. Manitoulin member.
- ×*Fenestella prisca* Lonsdale. Hall has this form from Flamborough Head. What he had can not be stated, but probably not *Semicoscium tenuiceps* (Hall).
- b**Callopora magnopora* Foerste. This Brassfield species of Ohio, Bassler and Parks identify from the Cataract. Of wide distribution near top of Cabots Head member.
- b**Homotrypa* (?) *confuens* (Foerste). Another Brassfield form of Ohio; also common in Cataract, in upper Cabots Head member.
- b+*Clathropora frondosa* Hall. This Rochester form is identified by Parks at Hamilton, in Cabots Head member.

BRACHIOPODA:

- **Lingula lingulata* Hall and Clarke. Original from Cabots Head member at Hamilton.
- +*Lingula clintoni* Vanuxem. This Clinton species also occurs near top of Cabots Head member.
- +*Lingula oblata* Hall. Parks identifies this Clinton species from Cabots Head member at Hamilton.
- b+*Dalmanella elegantula* (Dalman). Of wide distribution in Manitoulin and Cabots Head members.
- b+*Rhipidomella hybrida* (Sowerby). Of wide distribution in Manitoulin member.
- +*Rhipidomella circulus* (Hall). This Clinton species also occurs in Manitoulin and lower Cabots Head members and is of wide distribution.
- b+*Orthis flabellites* Foerste. This widely distributed Siluric form is also common in the Manitoulin and lower Cabots Head members. Identified by Nicholson as *O. calligramma davidsoni*.

× *Plectorthis medinaensis* Grabau (nom. nud.).¹² Niagara River Gorge. Is probably one of the two following species of *Hebertella*.

b* *Hebertella fausta* (Foerste). This Brassfield form also occurs in the Manitoulin member.

b* *Hebertella* cf. *daytonensis* (Foerste). This Brassfield form may also occur in the Manitoulin member.

b+ *Platystrophia biforata* (Schlotheim). Common in Manitoulin member.

b+ *Plectambonites transversalis* (Wahlenberg). At times common in Manitoulin member, as at Hamilton.

b+ *Leptæna rhomboidalis* (Wilckens). Of wide distribution throughout the two upper members of the Cataract.

b+ *Schuchertella subplana* (Conrad). This Siluric form also occurs rather rarely in the Manitoulin member.

* *Atrypa*, n. sp. This large and fine multistriate form of the *A. marginalis* group occurs in the Manitoulin member at many localities, especially at Dundas.

++ *Atrypa rugosa* Hall? A form similar to this species occurs at many localities in the Manitoulin member.

* *Cælospira planoconvexa* (Hall). Originals from Flamborough Head as *Atrypa planoconvexa*. Restricted to Manitoulin member and the best guide to the Cataract.

Whitfieldella, 2 sp. A small form that is common in the Manitoulin member. Another larger form is less often seen and has been identified as *W. naviformis*, a Clinton species of New York.

m* *Whitfieldella* cf. *oblata* (Hall). This may be the Upper Medina *W. oblata*. It occurs rarely in the Manitoulin and Cabots Head members at Cataract and Stony Creek.

× *Hyattidina congesta* (Conrad). Hall (1852) identifies this form as *Atrypa congesta*, from Flamborough Head. As no one has since seen this fossil in the Cataract, it seems probable that an error was made here. In the lower Manitoulin at Hamilton occurs a *Whitfieldella* that may have been identified as that form. As *Hyatella* is preoccupied, Schuchert in 1913 changed it to *Hyattidina*.

m+ *Camarotoechia neglecta* (Hall). This widely distributed form is common throughout the two upper members of the Cataract.

* *Camarotoechia janea* (Billings). In Manitoulin member, Manitowaning.

+ *Uncinulus stricklandi* (Sowerby).¹³ Niagara River Gorge. In all probability not the higher Siluric *U. stricklandi*.

PELECYPODA:

m* *Modiolopsis* (?) *orthonota* (Conrad). This Medina form also occurs at the top of the Whirlpool member and in the Manitoulin.

m* *Pterinea* (?) *primigenia* (Conrad). This Medina species is also in the upper part of the Cabots Head member.

GASTROPODA:

+ *Cyclonema cancellatum* (Hall). This Clinton form also occurs in the Manitoulin member of the Cataract.

¹² Loc. cit.

¹³ Grabau: Loc. cit.

bm+*Bucanopsis trilobata* (Conrad). In the Manitoulin and Cabots Head members at Hamilton; also in Medina and Clinton.

++*Platystoma* cf. *niagarense* Hall. Small specimens rare in Manitoulin member at Cataract and elsewhere.

OSTRACODA:

m**Isochilina cylindrica* (Hall). This Medina form or a very similar one also occurs rarely in the Manitoulin member.

TRILOBITA:

×*Calymene niagarensis* Hall? Fragments are common in the Manitoulin member. May turn out to be *C. vogdesi*.

×*Dalmanites*, sp. undet.¹⁴ Niagara Gorge.

b+*Encrinurus* cf. *punctatus* Wahlenberg. Fragments of two species of *Encrinurus* occur in the Manitoulin member.

×*Acidaspis* sp. Manitoulin member at Hamilton.

×*Lichas* sp. Manitoulin member near Collingwood.

THE MEDINA FORMATION

In the second part of this paper the history of the Medina formation is given, and it is there shown that although Vanuxem was the first to use the name in print, the credit rightly belongs to Hall and dates from 1840. The name then embraced a great thickness of red sandy shales and some sandstones, constituting the lower and the greater part of the formation, which is terminated by variegated sandstones and shales. This definition of the Medina was retained everywhere until 1905, when Grabau split the formation into two series, referring the lower red shales to the Ordovician as the shore phase of the Richmondian. Subsequently, in 1908, he named these shales the Queenston (synonym Lewiston, Chadwick, 1908), retaining the name Medina for the upper sandstones and shales, the only part that had been characterized by fossils. This procedure was altogether correct, for we now know that the Queenston is the easterly and shore phase of the Richmondian, a fact that can be seen by any one who will take the time to study these deposits from Niagara Falls northwestward to the Manitoulin Islands, at the north end of Lake Huron. In the east not a single fossil is to be had in the entire formation other than the burrows *Palaeophycus tortuosum*, but gradually more and more appear from the base upward as we proceed to the northwest, until finally the entire red beds have changed through lateral transition into bluish calcareous shales and thin limestone replete with Richmondian fossils. Under these circumstances the Queenston must be separated from the higher sandstones, leaving the latter as the typical expression of the Medina, for at Medina along Oak Orchard Creek one practically sees only these red and white sandstones characterized by the well known

¹⁴ Grabau: Loc. cit.

fauna first developed by Conrad and later supplemented by Hall. We can no longer use the term Medina in the old sense to include the Richmondian and Medina *sensu stricto*, since by general consent through a half century of geologic endeavor the line distinguishing the Ordovician from the Silurian has been drawn in America and Europe at the top of the Richmondian and its equivalents, and beneath the fossiliferous Medina (or at least so by inference) or lower formations having the faunal impress of Silurian time. The two series of deposits are marked by dissimilar faunas and are separated by a time break, to which hiatus no formations are as yet referable as having faunas that will bridge the life of the Richmondian (Ordovician or Cincinnati) and the Medina. For these contacts see plate 13, figures 1 and 2, and plate 14, figure 2. Even if such transition faunas were at hand, it would then not necessarily follow that the Richmondian is better placed in the Silurian system. It remains for those departing from the old and accepted classification to show the desirability for this striking change.

Grabau is also correct in restricting the term Medina to the upper or sandy Medina of Hall, and there was therefore no need for Clarke to propose Albion to take its place, as he has recently done; the term is, however, adopted in the lately published Niagara folio.¹⁵ Even if it were necessary to use another name than Medina, Oneida of Vanuxem could well have been made to serve this purpose. On the other hand, the writer well understands why Albion was proposed, this being due to the view that Queenston and Richmondian are better referred to the Silurian than to the Ordovician. This opinion is, however, at variance with all previous classifications and the writer has heretofore protested against it. He is prepared to show that the opinions of the older stratigraphers in America and Europe are correct in their general premises, and, further, that on the principle of diastrophic movement and faunal dissimilarity the Silurian invasion did not begin with the Richmondian, but rather, as so long held and without dissenting opinion, at the base of the fossiliferous Medina or other older formations that are clearly younger than Richmondian—for example, Lyckholm and Borkholm of Estland, Etage 5 of Norway, Trinucleus beds of Sweden, or Keisley of Britain.

If we are to be purists in nomenclature and strict adherents to the rule of priority, then Conrad's term Niagara sandstone of 1836 (see Part II for detail) clearly has right of way over Medina *sensu stricto*. Hall should have adopted this term, as he gives evidence that he knew of its existence; but, as is well known, he was a great and forceful leader, never

¹⁵ Kindle and Taylor: Geol. Folio No. 190, U. S. Geological Survey, 1913, p. 6.
Why Kindle did this is explained in Science, vol. 39, 1914, p. 915.



FIGURE 1.—CONTACT OF THE CATARACT (WHIRLPOOL) SANDSTONE ON THE BRICK RED QUEENSTON SHALES

Exposure along the Grand Gorge Railway, Niagara Falls, New York



FIGURE 2.—CONTACT OF THE CATARACT (WHIRLPOOL) SANDSTONE ON QUEENSTON SHALE

Stony Creek, Ontario, Canada

CONTACTS BETWEEN SILURIC AND ORDOVICIC (CINCINNATIC) SYSTEMS



FIGURE 1.—MEDINA SANDSTONE AND CATARACT (CABOTS HEAD) SHALE CONTACT AT HAMILTON, ONTARIO, CANADA

Note the wave-rolled layer in the Medina. Photographed by Merton Y. Williams



FIGURE 2.—CATARACT (MANITOULIN) DOLOMITE RESTING ON RED QUEENSTON SHALES, 2 MILES WEST OF CABOTS HEAD, GEORGIAN BAY, ONTARIO, CANADA

Photographed by Merton Y. Williams

CONTACTS OF THE CATARACT IN ONTARIO, CANADA

a follower. Then, too, he was the first American to lay down in writing the rule as to how formation names should be proposed (see quotation in Part II), and as he then said nothing about priority, and as this second rule was not formulated even by the biologists until 1844, we may overlook his neglect in accepting Conrad's term. To do otherwise now would bring on more confusion than clarity, because in 1842 and 1843 Vanuxem and Hall both used the same name, Niagara, for a group term of wide acceptance at present to embrace the Rochester shale and Lockport limestone.

Further, the term Cayuga sandstone (Vanuxem, 1839) is older than the accepted Oneida conglomerate (Vanuxem, 1840) and even than the Medina of Hall, and Oswego sandstone (Vanuxem, 1839) could well have been made to serve the place now taken by Queenston (Grabau, 1908). Most of these terms are, however, still of use to express local facies differences, but for time terms we should now disregard the rules and use here the younger names, Queenston and Medina. The "gray band" of Eaton, at the top of the Medina, is now known as the Thorold member,¹⁶ while the basal white sandstone along the Niagara River is well named Whirlpool sandstone.¹⁷ It will be shown that the latter is a member, not of the Medina, but of the Cataract formation, a series of calcareous sediments that in passing southeastward through Ontario gradually merges into a part of the sandy and fossiliferous Medina.

The Medina is typically developed along Oak Orchard Creek, which runs through the town of Medina. Here the formation is about 60 feet thick; it is described in detail in the second part of this paper. This thickness and the physical characters are about the same all the way from Rochester, which is 40 miles east of Medina, to Niagara Falls, an additional distance of 35 miles. At the last named place, however, the Cataract formation, 54 feet in thickness, is wedged underneath the upper Medina, consisting of the basal Whirlpool sandstone 22 feet thick, followed above by 32 feet of green shales, with a little of impure magnesian limestone. In all the sections from Niagara Falls eastward to Rochester there is a basal white, more or less coarse sandstone; but as it is clearly tangential in space and time, it is wrong to call it at all these places the Whirlpool sandstone. Certainly east of Lockport none of the basal sandstones hold the time of that along the Niagara River. From Niagara Falls northwestward the Whirlpool sandstone is far less or almost not at all tangential in time, and the name can be applied, without doing violence to correlation, to the basal sandstones in all of these sections.

¹⁶ Kindle and Taylor: Op. cit.

Grabau: Bull. Geol. Soc. Am., vol. 24, 1913, p. 460. Here Thorold quartzite.

¹⁷ Grabau: Jour. Geol., vol. 17, 1909, p. 238.

The Medina formation as here restricted may be described as follows:

Thorold member or gray band, 2 to 8 feet thick. This is nearly always a white, cleanly washed, more or less resistant, thick-bedded sandstone. No fossils are known from it other than the sand fillings in sun-cracks, which are more or less water-rilled, such as are seen at Medina and were described by Conrad in 1838 as *Dictuolites beckii*.

The *Upper Medina* is composed of red, cross-bedded sandstone, more or less impure intraformational shale pebble conglomerates, and some red shales, with a thickness of from 8 to 15 feet. These beds are marked by the burrows *Dadalus archimedes* and *Arthropycus alleghaniense*.

The *Middle Medina* consists of thin-bedded sandstones and shales, more or less red in color, with some white sandstones. The amount of coarse sand is variable in the sections, most abundant east of Lockport, and with more shale at this place and at Niagara. The thickness in eastern sections is about 20 to 25 feet and about 40 feet at Niagara, where there is, however, no basal sandstone. The Medina brachiopod and molluscan fauna listed elsewhere is from this zone, and especially from Medina. *A. alleghaniense* may occur in the upper half of this zone.

The *Lower Medina* is made up of basal, thick-bedded, coarse, cross-bedded, more or less red and dirty sandstones, though in places white and fairly clean. Thickness, about 20 feet. This rests with a very even base on the Queenston. Fossils are very scarce and of no significance.

THE MEDINA FAUNA

Because of the sandy, shifting nature of the Medina formation the fauna, of a very shallow sea, is not a large one. *Lingula cuneata* is often found in pure white sandstones and always as single valves washed about by the waves. Very little else is found associated in such deposits, though a bivalve may also be present and as well *Isochilina cylindrica*. In less clean sands the vertical spiral or lamellar burrows of *Dadalus archimedes* occur in great quantity; but as a rule this form and *Arthropycus alleghaniense* prefer dirty sands, while the latter and the so-called fucoids are most often seen in the dirtiest of sandy beds in thin shale partings. The bivalves and ostracods also preferred the dirty sands, but all have been washed about by the waves, while the calcareous shelled brachiopods, gastropods, and cephalopods occur in very thin zones that are more or less limy, though dirty and sometimes even decidedly ferruginous.

The fauna was originally described by Conrad¹⁸ and by Hall,¹⁹ and is, with subsequent additions, listed below. Some of the species listed by

¹⁸ Second and Third Repts., N. Y. State Geol., 1838 and 1839.

¹⁹ Geol. N. Y., Fourth Dist., 1843, pp. 36-57.

Pal. N. Y., vol. II, 1852, pp. 4-14.

Grabau²⁰ are now referred to the Cataract formation. The localities given are the type localities for the species, and the symbols are as follows: * = restricted to Medina formation, × = of no stratigraphic value, + = also in higher formations, ++ = affinity upward, and c = also in Cataract.

PROBABLE BURROWS:

× *Fucoides heterophyllus* Hall, 1843, 1852. Rochester.

× *Fucoides auriformis* Hall, 1843, 1852. Rochester and Medina.

BURROWS:

c× *Scolithus verticalis* Hall, 1852. Monroe County.

× *Palaeophycus tortuosum* Hall, 1852. Rochester. These forms occur only in the upper portion of the Queenston and are burrows that are badly distorted by consolidation of the muds.

* *Dadalus archimedes* (Ringueberg). Lockport. As *Spirophyton archimedes* (see Sarle, Proc. Rochester Acad. Sci., 4, 1906: 203). Described by Hall as *Arthropycus* sp. (Pal. N. Y., II, 1852: 6, pl. 2, fig. 2).

* *Arthropycus alleghaniensis* (Harlan). Tuscarora sandstone, 10 miles east of Lewiston, Mifflin County, Pennsylvania. The following is the synonymy:

Fucoides alleghaniensis Harlan, Jour. Acad. Nat. Sci. Phila., 6, 1831: 289, pl. 15, figs. 1-3.

Fucoides alleghaniensis Harlan, Med. and Phys. Researches, 1835: 393, fig. 1.

Fucoides Brongniartii Harlan, ibid.: 398, fig. 2.

Encrinurus giganteus Eaton, Geol. Text-book, sec. ed., 1832: 37, pl. 1, fig. 8.

Fucoides harlani Conrad, Second Ann. Rept., N. Y. State Geol. Surv., 1838: 113 (not defined, but *F. brongniartii* cited as syn.).

Fucoides harlani Hall, Geol. N. Y., Fourth Dist., 1843: 46, figs. 1, 2.

Arthropycus harlani Hall, Pal. N. Y., II, 1852: 5, pl. 1, fig. 1; pl. 2, figs. 1a-c.

Arthropycus alleghaniensis Sarle, Proc. Rochester Acad. Sci., 4, 1906: 203.

BRYOZOA:

× *Pachydictya*, sp. undet. A fine large foliar form with pointed monticules. Lockport. Original in American Museum of Natural History.

× *Trepodomata* Bryozoa. Medina. One or more species in American Museum of Natural History.

BRACHIPODA:

* *Lingula cuneata* Conrad, 1839 (Third Ann. Rep.: 64). Medina.

++ *Schuchertella*, sp. undet. This species is identified by Whitfield as *Strophonella* (?) *orthididea* of the Clinton. The originals are in the American Museum.

++ *Camarotoechia* (?) *plicata* (Hall), 1852. Lockport. May be related to *Rhynchotrete cuneata* of the higher formations.

²⁰ Loc. cit.

c+*Camarotæchia neglecta* (Hall)? Specimen in American Museum. Occurs also in Cataract and Niagaran.

c**Whitfieldella oblata* (Hall), 1852. Lockport. Closely related to Clinton forms.

PELECYPODA:

c**Pterinea* (?) *primigenia* (Conrad), 1839. Medina. Syn. *Cypricardia alata* Hall, 1852: 11.

**Pterinea*, n. sp. Related to last species. Lockport and Medina.

c**Modiolopsis* (?) *orthonota* (Conrad), 1839. Medina.

GASTROPODA:

**Pleurotomaria* (?) *pervetusta* (Conrad), 1839. Medina.

**Liospira* (?) *litorea* (Hall), 1852. Lockport.

**Liospira*, n. sp. Much higher spire. Medina. American Museum.

**Holopea* (?) *conoidea* (Hall), 1852. Lockport.

c+*Bucanopsis trilobata* (Conrad), 1839. Medina. Also in Cataract and Clinton.

CEPHALOPODA:

×*Orthoceras multiseptum* Hall, 1852. Lockport.

×*Oncoceras gibbosum* Hall, 1852. Lockport.

OSTRACODA:

c**Isochilina cylindrica* (Hall). Medina.

RELATIONS OF THE CATARACT TO OTHER SILURIC FAUNAS

Species of the Cataract fauna.—The Cataract fauna so far as determined has about 76 species, but when all of the material so far collected is worked up the number will certainly exceed 100 forms. Enough is now known, however, to indicate clearly the relationships of this early Siluric fauna.

Relation to the Medina.—In common with the Medina, the Cataract has 7 species, and when one notes that the latter is essentially a limestone fauna and the former one of sands, the stratigraphic significance of these figures is apparent. However, it will be better to reverse the statement, and say that of the 22 forms constituting the Medina biota, 7 are also found in the Cataract. These are (1) *Scolithus verticalis*, (2) *Whitfieldella oblata* (not yet established), (3) *Camarotæchia neglecta*, (4) *Modiolopsis* (?) *orthonota*, (5) *Pterinea* (?) *primigenia*, (6) *Bucanopsis trilobata*, and (7) *Isochilina cylindrica*. These fossils show that the two formations are probably nearly of one time, although species 1, 3, and 6 have little stratigraphic value. The guide fossils restricted to the Medina are (1) *Dædalus archimedes*, (2) *Arthropycus alleghaniense*, (3) *Lingula cuneata*, (4) *Pleurotomaria* (?) *pervetusta*, and (5) *Holopea conoidea*. We may state the evidence in another way by saying that the Medina biota has 22 forms, and of these 6 have no stratigraphic significance. This leaves 16 species, of which 7 are also in the Cataract, 7

are restricted to the Medina, and 2 either pass into the Clinton or have close relations with forms of this fauna; the total number, however, that persists into the Clinton is 4. These statements indicate that the Medina is more closely related to the Cataract than to the Clinton.

It should also be stated that the Medina is of the Appalachian province, while the Cataract is either of the St. Lawrence or of the Arctic realm. These waters came in over the continent from different oceanic areas and accordingly have different organic associations. Hence the similarity of the biotas can not be close, and this, with the marked difference in sedimentation, gives additional reason why considerable weight is laid on the forms held in common, as showing that both formations are the deposits of about one time.

Relation to the Brassfield.—The Cataract may also be compared with the Brassfield formation of Ohio and Indiana, as the two are clearly related, and also as both are of a limestone facies. The former has 76 species and the latter 140.²¹ Between the two there are 24 forms in common, and of these the following have the most significance in correlation: *Clathrodictyon vesiculosum*, *Acervularia* (?) *gracilis* (in Ohio, *A. clintonensis*), *Rhinopora verrucosa*, *Phænopora ensiformis*, *Callopora magnopora*, *Homotrypa* (?) *confluens*, and *Hebertella fausta*. When the two biotas are finally carefully compared with each other, there will undoubtedly be added more significant forms, strengthening the view that the Cataract and Brassfield are fairly close correlates in time. However, as these two faunas are not of the same epicontinental basin, one can not expect a large percentage of the forms to be common to both; the Brassfield element came in from the Gulf of Mexico region, while the Cataract migrated into Ontario through the Gulf of St. Lawrence embayment across the Province of Quebec or came in from the Arctic. The Brassfield is marked by the guide fossils *Triplecia ortonii* and *Stricklandinia triplesiana*, forms never seen in the Cataract, while the latter has as its markers *Helopora fragilis*, *Rhinopora verrucosa*, *Rhipidomella circulus*, *Atrypa* n. sp., and *Cælospira planoconvexa*. On the other hand, both are closely related to the Clinton, for of the Cataract fauna fully 30 species pass upward and about the same percentage (40 per cent) from the Brassfield.

That the Cataract is a close correlate with the Medina has been shown, and that it is equally so with the Brassfield can be brought out in still another way. The Cataract fauna has 76 forms, and of these 22 have no stratigraphic significance (those marked X and the Errant Annelida).

²¹ Foerste: Geol. Surv. Ohio, vol. vii, 1893, pp. 516-601, pls. 25-37a.

Of these 54 species, 24 also occur in the Brassfield, 7 in the Medina, 10 are restricted, while 30 pass upward into the Clinton or higher formations.

Relation to the Siluric of Anticosti.—The Cataract does not readily correlate with the Anticosti section²² because of the marked differences and generalized character of the faunas there, and more especially because of the long range of most of the species. With the Becsie River, the only guide fossil in common is *Cælospira planoconvexa* (appearing about 70 feet above the base of the Becsie River); but the Anticosti individuals are only half grown compared with those of the Cataract, a condition seemingly in harmony with the conclusion that the latter are of a younger time. Then the absence in the Cataract of the Becsie River guide, *Clorinda barrandei*, also seems to indicate that the former formation is of younger age. At the top of the Becsie River, however, the fauna is more like that of the Cataract, and this similarity continues in the succeeding 300 feet of the Gun River formation.

On the other hand, the Brassfield of Ohio correlates more readily with the Anticosti section and apparently best with zone D₈ of the Gun River, which is from 240 to 305 feet above the Becsie River. It is here that *Triplecia insularis* (compares with *T. ortonii* of Ohio) and *Stricklandinia lens* (compares with *S. triplesiana* of Ohio) appear for the first time. That the correlation can not be made with the next higher zone, D₉, is attested by the presence here of *Atrypa reticularis*, *Pentamerus oblongus*, and *Cælospira hemispherica*, species that in New York and Ontario are not seen below the Clinton. For these reasons, then, it may be said that the Brassfield, Cataract, and Medina seem to hold the horizon of the lower part of the Gun River formation, or more exactly from D₆ to D₈, a thickness of 178 feet. From these statements it will be seen that this correlation is different from that by Schuchert and Twenhofel in 1910, where the "Ohio Clinton," now the Brassfield, was correlated with the zones D₉ and E₁₋₃. Further, the Medina was then doubtfully placed beneath the Brassfield and correlated with most of the Gun River, whereas now, by regarding the Medina and Brassfield as equivalents of each other and of the Cataract, and with a better knowledge of all three formations, it appears better to regard them as equivalents of zones D₆ to D₈ of the Gun River formation.

CONTACTS BETWEEN THE MEDINA, CATARACT, AND CLINTON

At Rochester, where the Clinton appears to be fully represented, there seems to be no break in deposition, or at least a very slight one, between the Medina sandstone and the lowest member of the Clinton—the Sodus

²² Schuchert and Twenhofel: Bull. Geol. Soc. Am., vol. 21, 1910, pp. 704-710.

shale. The contact here is sharp and without transition from the sandstone into the shale. Farther east the transition in the character of the sediments is said to be more gentle and complete, and this condition probably obtains throughout Pennsylvania and Maryland. In the latter state, at Cumberland, a complete and gradual transition can be seen, and it is clear that *Caelospira hemispherica* gradually appears and finally dominates the Clinton there.

At Rochester the Clinton consists of four members. From below these are the Sodus shale (24 feet), Wolcott limestone (14), Williamson shale (24), and Irondequoit limestone (18). At Medina, which is 40 miles west of Rochester, the Sodus has thinned to 3 feet, and although there is a basal Clinton shale, sometimes called Sodus, farther west, there is no proof that it holds the time of this member as developed at Rochester. In the Niagara gorge the Clinton, of continuous deposition, is 30 feet thick and represents the time from the Irondequoit to the Wolcott, as no intermediate shale representing the Williamson is developed here or to the westward. Going farther west and then north along the Niagara escarpment, the Clinton limestone gradually pinches out and none is present north of Glenwilliam. In this region the higher Rochester shale pinches out in the same way and none is seen north of Limehouse. For these reasons the Lockport dolomite in these northern sections comes to rest directly on the Cataract, and there is here, therefore, an easily discerned disconformity, indicating a time break of considerable length. [Grabau as censor of this paper thinks there is no break here, only a lateral sedimentary change from the Rochester shale to the limestones of the Lockport type. In the same way he explains the broken contacts between the Medina and Clinton. To these views the writer does not assent.] To the southeast the break becomes less and less long and from Thorold and the Niagara gorge east to Rochester, while the contacts are uneven, with the basal Lockport sediments disturbed and wave-rolled, still there appears to be no break in sedimentation between the Rochester and Lockport.

On the other hand, the Medina at Rochester is about 60 feet thick, and this depth is maintained to Lockport; but in the Niagara Gorge the thickness is usually given as about 120 feet. A reexamination of this famous Siluric section shows that about 54 feet are referable, on the basis of fossils, to the Cataract, so that the Medina as here restricted has the regulation thickness of about 60 to 65 feet. The contact between them is easily determined, as the Medina is always a sandstone resting on the Cataract shales (see plate 14, figure 1). In tracing the Medina to the northwest, it is seen to pinch out as do the Clinton and Rochester, and is observed for the last time at Dundas, with about 8 feet thickness. The

contacts in this area are always easily made out—a sandstone on a shale. As the Medina thins out to the northwest, so the Cataract thickens in the opposite direction, being 54 feet in the Niagara Gorge, 80 feet at Grimsby, 90 feet at Stony Creek, Hamilton, and Dundas, and 105 feet or more to the northwest.

At first the writer interpreted these sharp contacts as disconformities; but he now sees, on the basis of the faunal evidence, that this interpretation is not the correct one. Further, the Stony Creek section shows practically a complete and sandy transition from the Cataract into the Medina. In other words, the top of the Medina—that is, the typical Medina, about 60 feet thick—gradually loses its sandy character from Thorold northwestward and is transformed first into sandy shales and then into argillaceous shales, the Cabots Head or topmost member of the Cataract. On the other hand, the two lower members of the Cataract—the Whirlpool sandstone and the Manitoulin limestone—maintain their Ontario petrologic characters into the Niagara Gorge (see plate 13 and plate 14, figure 2). Finally, the latter member is either absent or modified at Lockport, while farther east both are absent. As the Medina and Cataract have at least 7 species in common, the easily discerned contacts between these formations as seen from Niagara Gorge to Dundas can not be interpreted as disconformities. In other words, the typical Medina formation shades through lateral alteration into the typical Cataract.

Even though the Medina, Cataract, and Brassfield are correlates of one another, it does not follow that each one is wholly the equivalent of any other. Each formation invades eastern North America from a different direction and each one has its own peculiar faunal assemblage (see figure 1). They therefore represent three physical provinces and marine basins. The Medina is of the northern Appalachian province; is a sandstone formation, and finally invades to a slight extent the area of the Cataract. The Brassfield province lies in the main west of the Cincinnati axis, is of southern origin, with limestone-making seas, spreads also up the southern portion of the Appalachian province, and finally invades slightly the area of the Cataract sea. On the other hand, the Cataract province spreads westward through the Saint Lawrence embayment, and finally in eastern Ontario and northeastern Ohio (known from the Clinton oil wells) unites with the other two provinces; but as the Medina waters form a shoal sandy area in northeastern Ohio between the other two provinces, very few of the species of either area intermigrate. Probably it would be more correct to state that the normal marine junction of the Cataract and Brassfield seas is prevented by the Medina delta. For these reasons Medina, Cataract, and Brassfield are to be retained as names for independent marine faunas and formations.

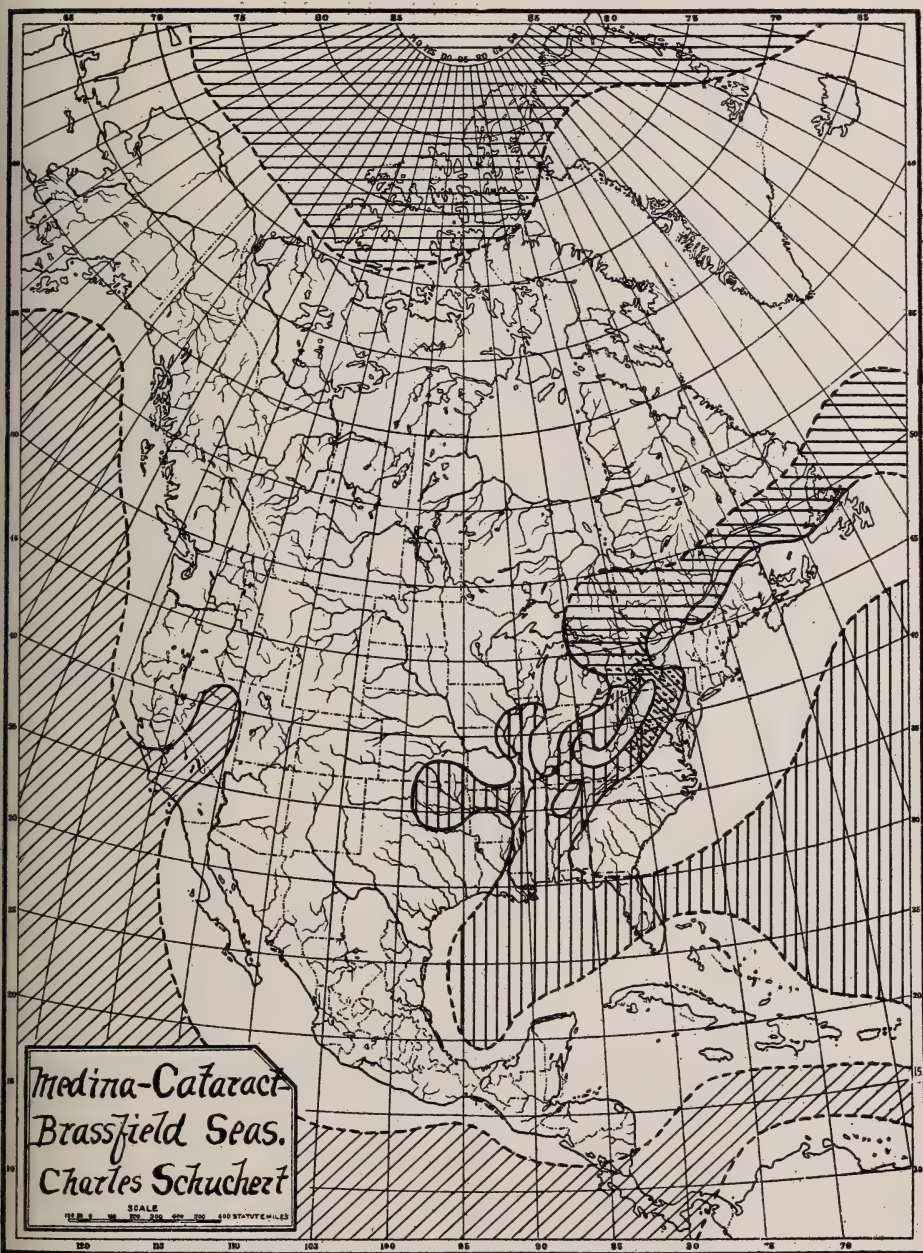


FIGURE 1.—Paleogeography of Medina (diagonal lines), Cataract (horizontal lines), and Brassfield (vertical lines) Seas

SUMMARY OF SECTIONS 340 MILES APART

0 = not present, × = present but thickness not determined, double lines = section broken

	Lockport		Rochester	Clinton				Medina	Cataract			Queenston	Richmond
	Lockport	De Cew		Irondequoit	Williamson	Wolcott	Sodus		Cabots Head	Manitoulin	Whirlpool		
Rochester, New York	125	2-5	85	18	24	14	24	60	.....	.....	.....	900	.....
Medina, " (40 miles west)	.....	.....	.....	10-15	.....	.....	3	65	.....	.....	.....	×	.....
Lockport, " (15 " ")	150	5	60	10-15	0	12-21	0	53	0	0	17	×	.....
Niagara gorge, " (20 " ")	150	6-9	60	10-15	0	12-21	0	65	32	.....	22	1085	.....
Thorold, Ontario (10 miles west)	×	×	71	10	0	16	0	×	.....	.....	6	.....	.....
Grimsby, " (20 " ")	×	8	39	4	0	10	0	25	74	.....	.....	×	.....
Stony Creek, " (10 " ")	×	?	25	4	0	9	0	18	70	8	12	×	.....
Hamilton, " (6 " ")	×	?	15	4	0	10	0	12	50	30	10	×	.....
Dundas, " (5 " northwest)	170	0	6	5	0	9	0	8	76	9	8	535	.....
Limehouse, " (25 " north)	×	.....	.....	.....	.....	6.5	.....	.....	×	.....	.....	×	.....
Glenwilliam, " (5 " " )	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	12	×	.....
Cataract, " (8 " " )	.....	.....	.....	.....	.....	.....	.....	.....	65	25	16	×	.....
Collingwood, " (48 " northwest)	160	.....	.....	.....	.....	.....	.....	.....	20	12	0	45	.....
Owen Sound, " (38 " west)	×	.....	.....	.....	.....	.....	.....	.....	75	30	0	50	×
Cabots Head, " (53 " northwest)	165	.....	.....	.....	.....	.....	.....	.....	45	15	0	45	×
Manitowaning, " (45 " ")	240	.....	.....	.....	.....	.....	.....	.....	27-66	50-60	0	0	435

PART II

HISTORY OF THE MEDINA FORMATION

Amos Eaton.—This pioneer geologist of New York, who was the first to write of the rocks now under discussion, states in 1824²³ that he was the first “who attempted a particular classification of American rocks,” and justifies his ability to do this with the statement that he had then taught over two thousand pupils in geology, and “had travelled more than three thousand miles on foot, and two thousand by water and carriage conveyance, in search of geological facts,” before he came under the patronage of Hon. Stephen van Rensselaer. “I have added more than five thousand miles of land and canal travelling, in pursuit of the same object, during the last four years,” he states as further proof of his ability.

In this old book we see applied to the Medina formation for the first time the names “Saliferous Rock,” “Grey Band (or Grey Feke),” and “Millstone Grit.” The term “Grey Band” is still in use, though recently Grabau (in Kindle) has proposed to replace it by Thorold sandstone. The Saliferous Rock, Eaton states, “is an aggregate of minute rounded grains of quartzose sand, or of minute argillaceous and quartzose grains, formed into red or greenish sandstone, or soft red or greenish brittle clay slate.” The gray band “is a hard fine-grained grey rock, which is so compact that it may be considered as homogeneous. It is a thin but continuous stratum, everywhere overlaying the red saliferous rock; and might be called *grey saliferous rock*.” Among the localities cited are Genesee Falls, Oak Orchard Creek, 4 miles west of Rochester to Lockport, and Lewiston; a number of other places are given where red rocks are exposed, but these clearly belong in the Salina formation, and from the occurrence of salt in these localities came the term Saliferous, a name somewhat though not entirely misapplied to the Medina. At Oak Orchard Creek are noted an abundance of stylasterites, “with very distinct transverse or torulose ridges.”²⁴ These are now known as *Arthropycus alleghaniense*.

The same formations and names appear in Eaton’s *Geological Text-Book*,²⁵ where they are classified as of the “Lower Secondary, or Third Series.” In the second edition of this text-book²⁶ Eaton is in doubt as to the proper disposition of the Saliferous in the geological column (he had included in it Queenston, Medina, and Salina, hence his trouble),

²³ Geol. and Agric. Surv. Erie Canal, N. Y., 1824, p. 9.

²⁴ Op. cit., pp. 12, 35-36, 102-116.

²⁵ 1830, pp. 39-40.

²⁶ 1832, pp. 65, 82-83, 94, 96, 120.

and he now refers it to a "Subordinate Series, embraced in the third Regular series (Lower Secondary)." Here again the gray band is placed as before, and he cites the same localities, with the addition of the Niagara River. The most interesting addition here, however, is that Eaton mentions *Lingula mytiloides* (= *L. acuminata*) and *Encrinurus giganteus* (described as new) as the fossils characterizing the "Saliferous." The latter turns out to be nothing other than the widely known *Arthropycus harlani* Conrad, though no one would readily come to this conclusion from Eaton's figure 8 on plate 1. It is defined thus: "*E. giganteus* (red coralline) branching, red or grey: often compressed, whirls uniform and generally obscure: branches of great length; mostly lying in the direction of the layers, or nearly so. Found in saliferous rocks at Oak Orchard, Mineral Hill in Blenheim, and a mile south of Mt. House [Catskills]" (page 37). The two last named localities must refer to something else and are not typical, for on page 83 he states: "I find the encrinurus giganteus in all of them; though the whorls are often indistinct or not manifest. They are most perfect at Oak Orchard Creek." This conclusion is confirmed on page 120. Eaton is, of course, in error in regarding these burrows as casts of the stems of crinoids.

T. A. Conrad.—We now pass over an interval of five years before another mention is made of the Medina formation. In 1836 the Geological Survey of the State of New York was authorized and organized, and in the following year was printed the first report. T. A. Conrad, who was appointed State Geologist of the Third District, reported on the Medina as follows:

"*Red or Variegated Sandstone of Niagara River.* We have chosen this name because it is descriptive of the only sandstone developed in the course of the Niagara River. . . . This widely distributed series of red and gray sandstones and shales has been termed 'saliferous rock' by Eaton, but it is by no means proved that it contains salt. . . . This formation is very interesting, in consequence of the peculiar and uniform nature of its organic remains." Those that he notes, however, are from Oak Orchard Creek at Medina. "The most striking feature in these sandstones and shales, is the vast abundance of fucoid, or marine plants, particularly that species termed *Fucoides Brongniartia* by Dr. Harlan. These penetrate every portion of the shale which constitutes the upper portion of the mass. . . . Testaceous remains are seldom found where fucoids are numerous, but immediately beneath the strata containing them, fresh water [an error which he recognizes and corrects in the Fifth Report, 1841, page 41] and marine shells abound in a limited space." They occur in "three narrow approximate veins filled with *Cyclostoma*,

Planorbis and *Unios* [also *Orthoceras*], and with marine depositions above and beneath them. . . . They occur below the fall in the banks of Oak Orchard Creek at Medina. Mingled with these, we find a few specimens of *Lingula* [*cuneata*], which just below are profusely disseminated through the rock. . . . All the larger layers are variegated with stripes of different hue, oblique to the plane of stratification, dipping at various angles and in different strata to opposite points of the compass. . . . Other fine sections of variegated sandstone are furnished by the Genesee River, north of Rochester, in the vicinity of the two lower falls" (pages 166-168).

Conrad's usage here of Niagara as a formation name is original, and that he intended the name to stand is proven by the Third Annual Report (1839, page 63), where in a table it is placed as "Niagara sandstone (red)," and more especially by the Fourth Report (1840, page 201). Under these circumstances, and according to the rules of formation nomenclature, it should have been adopted. In this case, it would have applied through characterization rather to the Medina sandstone than to the "red marl," now the Queenston, which was also included in his discussion of the section along the Genesee. In the Fifth Report (1841, page 31), however, Conrad seems to have forgotten his term Niagara sandstone, for here he writes "Red sandstone." In any case, to revive at this date the term Niagara for the Medina would displace the series term Niagara or Niagaran introduced by Vanuxem in 1842, and as this would cause more confusion than otherwise the writer does not care to make the substitution.

James Hall.—Conrad, after his first year as field geologist of the New York State Survey, became the State Paleontologist, and James Hall, a pupil of Eaton, was assigned Conrad's area in the western part of New York. In the Second Report (1838, pages 294-297, 357) Hall writes of the Medina, and the following extracts are taken from his report:

"*Red Marl and Sandstone.*" As may be seen above, Conrad had the year before called this formation the "Red or Variegated Sandstone of the Niagara River;" Hall now objects to the characterization "variegated" as "being already appropriated, as designating a member of the new red sandstone series. . . . Besides this, there are only a few of the upper strata which are variegated."

"The rock below the grayband is variegated to the depth of 20 or 30 feet, with gray or greenish gray spots and seams. Although this formation has been called sandstone, much the largest proportion of it is an indurated marl, containing too little siliceous matter to entitle it to the name of sandstone. On the Niagara River, where there are more than

five hundred feet in thickness developed, we find no more than forty feet of a siliceous character. . . . The marl in the lower part of the formation is striped, vertically and horizontally, with seams of green shale." It is therefore seen that Hall here follows the example of Eaton and Conrad in including the marl (= Queenston) and the higher sandstones (= Medina) all in one formation, a correlation that was continued until 1905.

"At Medina, about forty feet from the top of this rock, we find a stratum, two feet thick, of siliceous sandstone of a greenish gray colour, containing *Lingula*, *Cyclostoma*, *Planorbis*, *Unio* and *Cytherina*. . . . The points at which this formation can be most advantageously examined, are along the Genesee River, below Rochester, at Medina, Orleans County, and along the Niagara River, near Lewiston."

We now come to Hall's Third Annual Report (1839), important because it is here for the first time that the principle is defined as to how formations shall be named. The use of a geographic name of the locality where the formation is typically developed was not new with Hall; but to him we must give the credit in that he was the first American to see clearly what must be done in this matter and to act accordingly, so that stratigraphers thereafter might become more certain of what they described.

Hall relates that he traveled with his colleague, Vanuxem, for "several weeks in examination along the boundary line between the Third and Fourth Districts." Vanuxem, learned and conservative, a graduate of the School of Mines in Paris, had great influence over Hall, as the latter related to the writer in 1889. Undoubtedly the principle of a type locality was formulated by Hall during this association in the summer of 1838, and in his report of 1839 many of our formation names now in use take their origin. He says:

"Hereafter we shall be enabled to avoid collision and discrepancy in our descriptions, and to designate groups without confounding them with each other. We have also found the solution of many difficulties, in part arising from previous partial examinations, and also from the fact that the character of several rocks below the Onondaga limestone entirely or materially change in their eastern prolongation; and more especially after passing the longitude of Cayuga Lake. . . .

"Every one who has studied rocks even partially, is aware of the insufficiency of mineral or lithological characters for giving nomenclature, and the many errors into which he may be led, whether in his own researches or by the mistakes of others. So likewise in the present state of our knowledge, we are unable in all cases to give names from fossil

characters; for though without doubt every group embraces its peculiar fossils, yet in all localities these may not be so marked as to excite attention, and in some may possibly be absent. It thus becomes a desideratum to distinguish rocks by names which cannot be traduced, and which, when the attendant circumstances are fully understood, will never prove fallacious. The basis of this nomenclature is derived from localities; and the rock or group will receive its name from the place where it is best developed. For example, the rock denominated in the section [of the last report] calcareous shale, simply to distinguish it from the green argillaceous shales below, will be called Rochester shale. In lithological characters it is extremely like one far higher in the series, but the fossil contents are entirely different. This contains the *Asaphus caudatus*, *Trimerus delphinocephalus*, *Platynotus Boltoni*, besides species of *Orthis* and *Delthyris*, all peculiar to this rock, and the characters if studied and well understood at Rochester, will guide the observer in all subsequent examinations. The limestone at Lockport excavated for the passage of the canal, we propose to call Lockport limestone. At this place the rock possesses in an eminent degree the geodiferous character, which has hitherto given it its name; but this is quite inapplicable to the same rock where seen in Wayne County" (1839, pages 288-289).

In the Fourth Annual Report (1840, pages 374, 453-455) we meet for the first time with the term Medina in Vanuxem's report. Evidently he did not intend to stand sponsor for the name, as Medina is not in his geological district (Third), but is in Hall's Fourth District. Vanuxem writes: "*Medina sandstone*. Called in former reports the red sandstone of Oswego. Predominant colour red, more rarely whitish and greenish. This rock is confined to Oswego County, to the high grounds of Oneida at Florence village, and other parts of the town of Florence, and to the extreme north parts of the counties of Onondaga and Cayuga" (page 374).

Hall in the same report writes as follows: "Medina sandstone, red marl and shale. This rock is the lowest in the 4th District, it being found bordering the shore of Lake Ontario, from Niagara River to the eastern limits of Wayne County." He intimates that it rests on the Salmon River group, which is now known to be of Lorraine or Maysville age. The fossils mentioned are the regulation Medina species.

In the final report,²⁷ in 1843, Hall gives a general summary of the Medina, and here he notes as synonyms all the names given above and as well Niagara sandstone, but as to this latter name states nothing further. He says: "At Medina, on the Oak-orchard Creek, we have the best exposure of the mass which exists in the State, and hence its name.

²⁷ Geol. N. Y., Fourth Dist., 1843, pp. 24, 34-57.

The thickness here exposed is not greater than on the Genesee River, nor so great as on the Niagara at Lewiston, but it exhibits all its fossil types in the greatest perfection" (page 43). He then gives a generalized section of the Medina, separating it into four divisions as follows:

- (1) Grey-band of Eaton. "The grey or greenish grey terminal portion. . . . It always appears more or less as a part of the Medina sandstone, possessing the same lithological features." Thickness, 2 to 10 feet. = Thorold member of Grabau.
- (2) The main red sandstone mass. Red marls and sandstones "gradually passing into a more sandy form in the western portion of the district."
- (3) "Grey quartzose sandstone entirely distinct" from the grey-band. At Niagara Falls the basal sandstone, 25 feet thick, has been named the Whirlpool sandstone member. These three members were later called the Upper Medina and redefined as the true Medina by Grabau.
- (4) "Red marl, and marly or shaly sandstone." Later on this member was called the Lower Medina and the Queenston by Grabau, who referred it to the Ordovician as the equivalent of the Richmond and Lorraine of the Cincinnati series.

C. A. Hartnagel.—In 1907²⁸ Hartnagel gave a good account of the Medina (as defined by Hall) as exposed about Rochester. Here he divides it into the "Lower Medina shale" and the "Upper Medina sandstone and shale." The former, he states, extends east to Rome, and is underlain by the Oswego sandstone, while the latter goes 40 miles farther to Cherry Valley. East of Oneida County the Upper Medina is known as the Oneida conglomerate and has the characteristic fossil *Arthropycus alleghaniense*. The year before,²⁹ Hartnagel had clearly shown that the Oneida is equivalent to the Upper Medina, as the above mentioned fossil had been found near Utica, in the type section of the formation, near Verona, in Oneida County, and at the falls of the Oswego. "The presence of this fossil and the stratigraphic relations of the Oneida conglomerate as shown in the Mohawk Valley can leave no doubt of the upper Medina age of the Oneida conglomerate."

A. W. Grabau.—In his well known *Guide to the Geology and Paleontology of Niagara Falls and Vicinity*,³⁰ Grabau gives a good detailed description of the four members of the Medina and includes all in the Silurian system. In 1905³¹ he returns to this formation, separating the lowest or fourth member from the Medina proper and placing it in the Ordovician. He states that the Oneida and Medina "were not deposited in the open sea, but rather under peculiar conditions, *i. e.*, estuarine, if not

²⁸ Bull. 114, N. Y. State Mus., 1907, pp. 10-12.

²⁹ Bull. 107, N. Y. State Mus., 1906, pp. 34-35.

³⁰ Bull. 45, N. Y. State Mus., 1901, pp. 87-95.

³¹ Science, vol. 22, 1905, pp. 528-529, 532-533.

continental. . . . Moreover, it is now pretty well ascertained that the typical Oneida conglomerate of Oneida County is the time equivalent of the Upper Medina of the Niagara section, and that both probably should be united to the Clinton, while the lower 1,100 feet of the Medina of western New York may possibly represent the continental or estuarine phase of deposits, representing elsewhere the later Richmond period."

In 1908³² Grabau names the Lower Medina the Queenston, writing as follows: "The dividing line between Ordovician and Silurian is drawn at the base of the Upper Medina or the Medina proper [about 125 feet thick at Niagara River]. For the red Medina shales now recognized as of Ordovician age the name Queenston beds is proposed, from the town of that name on the Niagara River opposite Lewiston, where these beds are partly exposed." Later in the same year Chadwick³³ also names the Lower Medina, calling it Lewiston after Lewiston, Ontario, and regarding it as the equivalent of the Richmondian. With the Clinton the Upper Medina "might be merged without violence. In any case the (restricted) Medina falls within the Niagaran." Finally, in 1909,³⁴ Grabau ranges the Medina and Oneida of New York and the Tuscarora of Pennsylvania with the Clinton in the Silurian, while the Oswego of New York and the Tyrone (later renamed Bald Eagle because of preoccupation) are referred to the Lorraine; the Queenston and the Juniata are, in the main, regarded as of Richmond time, while "the lower part must be considered as Lorraine."

Lardner Vanuxem.—If we are to remain strictly by the law of priority in naming formations, we can not accept either Queenston or Lewiston, but must go back to Vanuxem, 1839,³⁵ and his term Oswego. To make this matter clear let us study Vanuxem in the original. He says: "*Red Sandstone of Oswego.* The red sandstone of Oswego is the lowest rock" of the counties "Madison, Onondaga and Cayuga. . . . From the eastern part of Oswego County, to the Niagara River, numerous brine springs are found in this red sandstone." The rocks which "appear from under the 'millstone grit' [= Oneida = Upper Medina], and from above the green shale of Herkimer . . . are the shales and green sandstone of Salmon River, and the red sandstone of Oswego." The latter appears "immediately under the 'grit.'"

Nor can we accept Oneida, for Vanuxem has named an equivalent in 1839:³⁶ "*Gray Sandstone of Cayuga.* To the south of the red sand-

³² Science, vol. 27, 1908, p. 622.

³³ Ibid., vol. 28, 1908, p. 347.

³⁴ Ibid., vol. 29, 1909, pp. 354-356; also Jour. Geol., vol. 17, 1909, pp. 234-238.

³⁵ Third Ann. Rept. N. Y. State Geol. Surv., 1839, pp. 244-246.

³⁶ Op. cit., pp. 242, 246.

stone, and reposing upon it, is a gray sandstone, the lower part often variegated with the red oxide of iron, and the upper variegated with green shale. . . . This mass for position corresponds with the 'mill stone grit' to the east and the 'gray band' to the west." "The 'millstone grit,' which is thirty and more feet in thickness in Herkimer and Oneida, gradually attenuates in going westward, being from four to five feet at Rochester. The materials of which this rock is formed, gravel and sand, prove that their source was eastwardly." It is in the following report (1840, page 374) that he proposes "*Oneida conglomerate*. The 'millstone grit' of Prof. Eaton, which has been changed, to do away with all ambiguity." Here it is, too, that Vanuxem lays aside his term Oswego for "*Medina sandstone*. Called in former reports the red sandstone of Oswego."

THE SILURIC SECTIONS IN DETAIL FROM ROCHESTER, NEW YORK, TO THE
HEAD OF LAKE HURON

Rochester, New York, section.—Examined by the writer in August, 1913. Use has also been made of Hartnagel, Bulletin of the New York State Museum, page 114, 1907, and Hall, Geology of New York, Fourth District, 1843, pages 58-117.

Lockport dolomite. Thickness present, 107-125 feet. The lowest beds are studied to best advantage in the large quarry on North Goodman street, where the Rochester is also worked for building stone (foundations). Here the lower 5 feet of the regulation Lockport consists at the top of fine-grained, dense, crystalline dolomite. Downward in this 5 feet appears more and more of sand, and finally the lowest foot or more is a regularly bedded, laminated, fine-grained, brittle sandstone. Beneath is a dark, bituminous, thin-bedded sandy shale, filling the hummocky depressions in the beds below. The same irregular contact may be seen at the Upper Falls of the Genesee.

De Cew member (Williams MS., 1914). The top of the Rochester is hummocky to the extent of at least 4 feet. Between these depressions and over the top of the ridges is deposited from 2 to 5 feet or slightly more of irregularly bedded (sea-churned) impure limy cement beds, not unlike the Rochester below.

Irregular wavy contact? Time break, if any, short.

Rochester shale. Thickness about 85 feet. At Rochester the formation has more lime and the strata are much harder and more resistant to weathering than at Niagara Falls, where there is less lime and the beds are more laminated into thin-bedded shales.

Clinton formation. Thickness about 80 feet.

Irondequoit limestone member, 18 feet thick. Thin-bedded limestones with shale partings. Locally between Rochester and Niagara Falls small Bryozoa reefs are developed near the top of this member, and some of these project several feet into the Rochester shale. Other-

wise the transition between the Clinton and Rochester is quick, but no break in sedimentation is apparent. Then, too, many of the species are common to both formations. Below there is a gradual transition into the

Williamson shale member, 24 feet thick. Thins rapidly to the west and is absent at Lockport. A green shale series at the top (8 feet), below which are more green shales (4 feet) with very thin pearly limestones replete with *Cælospira hemispherica*, and finally purplish and black shales (12 feet), the latter with *Monograptus clintonensis* and *Retiolites venosus* in abundance.

Wolcott limestone member, 14 feet thick. Thin-bedded greenish limestones that come in rather sharply over the Sodus shale, but shade into the Williamson. Three feet above the base occurs the *Furnaceville iron-ore*, here about 1 foot thick. It is decidedly cross-bedded, made up of fragmented and worn fossils, some sand, and less oolite; the fossils are crinoidal fragments, Bryozoa, and Tentaculites, all altered or coated with iron. The beds below the ore and the ore itself show wave action. *Pentamerus oblongus* (Clinton form) and *Hyattidina congesta* are guide fossils.

Sodus shale member, 24 feet thick. A green, fine-grained shale almost devoid of fossils, other than "fucoids" and trailings. It rests abruptly and without the least transition upon the Medina. The Sodus thins rapidly to the west and is only 3 feet thick at Medina.

Contact very sharp between adjacent beds. Probably no time break.

Medina formation. Thickness about 60 feet.

Thorold member, or "gray band." A massive white sandstone, 5 feet thick.

Heavy-bedded, channeled, red and mottled, dirty sandstones, with but little shale and many zones of intraformational shale pebble conglomerates, 15 feet thick, with *Dædalus archimedes* throughout and *Arthropycus alleghaniense* in upper 6 feet.

Regularly thin-bedded, lighter red sandstones, with more prominent shale partings, about 20 feet thick. *A. alleghaniense* and *Lingula cuneata* in upper 5 feet and much sun-cracking in upper 2 feet.

Basal thick-bedded, very coarse red sandstones, as follows: At the top 10 feet of irregularly bedded sandstones, followed by one bed 4 feet thick, also much cross-bedded, and then the basal zone of 6 feet, regularly bedded below, and cross-bedded and often deeply channeled above. Here again the sandstone fills into the sun-cracked surface of the Queenston below.

Disconformity. Base of Siluric.

Queenston formation. Top of Ordovician (Richmondian). There has been much uncertainty here as to the lower limit of the Medina, but the heavy, and much cross-bedded gray sandstones easily mark the base. The uncertainty is due to the fact that the Queenston is here much more sandy than farther west and that there are horizons of local sandstones. Still farther east these sandstones pass into the Oswego. Here the Queenston in the upper 40 feet consists of red, micaceous, sandy shales, with thin zones of gray localized sandstone. There are many

worm burrows, now distorted, squeezed, and slickensided, but none are of *Arthropycus*. These are *Palaeophycus tortuosum*. Then a shaly red sandstone, 10 feet thick, followed below by more red sandy shales.

Total thickness of Queenston, exposed and underground, is said to be about 900 feet.

Medina, New York, section (40 miles west of Rochester).—Hall, Geology of New York, Fourth District, 1843, pages 34-57.

Clinton.

Medina formation. At least 54 feet, but probably nearer 65 feet. The upper part is to be seen in the many quarries along the Erie canal and along Oak Orchard creek, while the lower beds are exposed below Medina Falls, to the west and northwest.

"Gray band." Hall says this is 4 feet thick. The zone from which came the originals of *Dictuolites beekii*, which are sand fillings in sun-cracks rilled by water.

A zone estimated to be 8 feet thick, not seen by the writer.

Thin-bedded dark red sandstones and a considerable amount of red sandy shales, 8 feet thick. Intraformational conglomerates of shale pebbles are common. Seen along the tow path of the canal. Two feet down occurs a zone 18 to 34 inches thick, made up of the spirals of *Dædalus archimedes* (in the creek above the falls this zone is 30 inches thick and made up of vertical plates only). *Arthropycus alleghaniense* occurs throughout the 8 feet. The lowest part of these beds is again seen at the top of the quarries.

Upper quarry level of thin-bedded red and pinkish sandstones with thin red shale partings, 15 feet thick. *A. alleghaniense* occurs here also in the upper half. In the lowest beds are found *L. cuneata* in abundance and *Modiolopsis* rarely.

Lower quarry level near the falls, of thin-bedded red sandstones with red shale partings, 10 feet thick. *Lingula cuneata* throughout these beds. In the top of this zone occurs the bulk of the described fauna, as *Pterinea* (?) *primigenia*, *Modiolopsis* (?) *orthonota*, *Pleurotomaria* (?) *pervetusta*, *Bucanopsis trilobata*, and *Isochilina cylindrica*.

White sandstones, sometimes slightly tinged with red blotches or faintly pinkish, about 21 feet thick. The upper 3 feet are thinner bedded, with shale partings, with the sandstones often replete with *L. cuneata*. Here also occur *Isochilina cylindrica*, *Modiolopsis* (?) *orthonota*, *Pterinea* (?) *primigenia*, *Pleurotomaria* (?) *pervetusta*, and *Bucanopsis trilobata*, all of which were originally derived from this locality and horizon. The greater central mass (12 feet) is more heavily bedded, with almost no shale (formerly quarried at the falls), while the lower 6 feet of thick beds (in places up to 10 feet) are much cross-bedded, of much coarser sand, with many black or greenish black streaks. All of the lower beds appear to be barren of fossils.

Disconformity. Base of Siluric.

Queenston brick-red shale. Top of Ordovician (Richmondian). At water-level some distance below the falls.

Lockport, New York, section (15 miles west of Medina).—The sequence here is difficult to make out because of the disconnected local sections. A visit in August, 1913, revealed the following:

Lockport dolomite. Thickness about 150 feet.

Gasport limestone member (Kindle, 1913), about as at Niagara gorge.

De Cew member (Williams MS., 1914). At the head of the "Gulf" near the brick-paved north-south road may be seen the basal beds. They are essentially like those in the Niagara gorge, with the upper contact line much more irregular than the lower one, which is fairly even with the Rochester shale. Thickness about 5 feet.

Irregular wavy contact. Time break, if any, short.

Rochester shale. About 60 feet thick. About as at Niagara gorge.

Clinton formation. About 30 feet thick, and as at Niagara gorge.

Disconformity. Sodus shale absent. [Grabau as censor questions the break here. He says it is another case of lateral change.]

Medina formation. Thickness about 53 feet without the basal sandstone, with it 70 feet. This formation was studied back of the United Indurated Pipe Co., along the stream, on the opposite bank, and finally in Whitmore quarries. The Medina is here essentially a very shallow water deposit with occasional preservation of the strand-line, or nearly so.

"Gray band," a white fine-grained sandstone, 2 feet thick.

Dark red thin-bedded sandstones and red sandy shales, 10 feet thick.

Arthropycus alleghaniense occurs at the very top and probably also throughout the entire zone.

Local zones of *Dædalus archimedes* (the type locality for this fossil).

Here in two beds with a combined thickness of 2.5 feet. In one horizontal direction these burrows were seen to vanish within 500 feet.

Red sandy shales, thin ferruginous mud bands, and red and white sandstones, with an estimated thickness of 30 feet. It is in the upper 20 feet that the Whitmore quarries are located, from which, in the red and ferruginous layers near the top of the quarry, the bulk of the Medina fauna of Lockport has been derived. From this zone and place Hall described *Rhynchotreta* (?) *plicata*, *Whitfieldella oblata*, *Pleurotomaria* (?) *litorea*, *Murchisonia* (?) *conoidea*, *Oncoceras gibbosum*, and *Orthoceras multiseptum*. The red sandstones are often replete with intraformational red shale pebble conglomerates in layers up to 4 inches thick. Some of the white sandstones abound in *Lingula cuneata*, and some of the layers have smooth beach-washed surfaces with stranded *Lingulas*, proving the shore conditions of deposition. The sandstones are a series of shallow lenses laid down in red muds.

Light greenish sandy shales alternating with thin sandstones, with an estimated thickness of 10 feet. No fossils were seen.

Basal white sandstone, 17 feet thick. The upper 11 feet are thin-bedded, while the lower 6 feet are massive. The under surface fills in the sun-cracked furrows of the Queenston below. May be equivalent to the Whirlpool sandstone.

Disconformity. Base of Siluric.

Queenston. Top of Ordovician (Richmondian). Four feet of this formation may be seen above the canal leading to the turbine of the Pipe Co.

Niagara Gorge, New York-Ontario, section (20 miles west of Lockport).—Along line of New York Central Railroad and Grand Gorge Trolley. See Grabau, Bulletin 45, New York State Museum, 1901, pages 87-95, and Kindle and Taylor, Geologic Folio 190, U. S. Geological Survey, 1913.

Lockport dolomite. Thickness about 150 feet.

The main upper mass of about 120 feet is a dark bluish gray to brownish colored, thin-and thick-bedded, more or less coarsely crystalline dolomite that is somewhat petroliferous and with geode cavities containing gypsum, selenite, dog-toothed spar, etc. In the highest beds are the precursors of the Guelph fauna, here always rare in species (see Clarke and Ruedemann, Mem. 5, N. Y. State Mus., 1903). The fossils include *Cœlidium macrospira*, *Pterinea subplana*, *Phragmoceras parvum*, etc. Otherwise the fauna is largely a modified Rochester assemblage.

Gasport member (Kindle, 1913). "Crinoidal limestone" or marble. Usually a non-magnesian limestone, but may also be transformed into a dolomite; replete with crinoidal fragments and local diagenetically changed Bryozoa reefs. From 7 to 20 feet thick. Fauna essentially that of the Rochester, with *Callicrinus*, *Ichthyocrinus conoideus*, *Eucalyptocrinus tuberculatus*, etc.

DeCew member. Drab to bluish gray, fine-grained, impure limestone or cement rock, that in the upper 3.5 feet is more or less strongly wave-worked, 6 to 9.5 feet thick. This horizon is in many places marked by irregular contacts, both above and below, and by the lithic differences between the adjacent formations. The upper contact is very regular, but the lower one is here decidedly irregular. No fossils. In some ways this member seems to be a transition zone under disturbed conditions from a shallow muddy sea to deeper limestone-making waters.

Irregular wavy (?eroded) contact. Time break, if any, short. [Grabau as censor questions the broken contact here. It becomes, according to the writer, more and more prominent to the northwest. The former states that it is another case of lateral change in the sedimentation.]

Rochester shale. About 60 feet thick.

The upper part of this formation has many thin layers of limestone replete with many species of Bryozoa described by Bassler (Bull. 292, U. S. Geol. Surv., 1906). The fauna gradually vanishes upward and in the uppermost beds there are almost no fossils.

The lower portion is all shale and is rich in fossils, especially toward the base. It has been described by Hall (Pal. N. Y., II, 1852) and is in the main derived from about Lockport. Much of this fauna appears in the Clinton below (Irondequoit). The more characteristic common fossils are *Caryocrinus ornatus*, *Stephanocrinus angulatus*, *Eucalyptocrinus calatus*, *Thysanocrinus liliiformis*, *Lyriocrinus dactylus*, *Ichthyocrinus levis*, *Dictyonella corallifera*, *Anastrophia interplicata*, *Rhynchotreta americana*, *Spirifer niagarensis*, *Trematospira camura*,

Dalmanites limulurus, *Homalonotus delphinocephalus*, *Lichas boltoni*, etc.

Clinton formation. Thickness about 30 feet.

Irondequoit limestone member, 10 to 15 feet thick. Very heavy-bedded, crystalline, crinoidal, pinkish gray limestone, with occasional Bryozoa reefs within and at the top of the limestone. In the latter case the reefs project several feet into the Rochester. Also has zones of stylolites. Transition into Rochester quick, almost abrupt. Fauna essentially that of the Rochester shale.

Wolcott limestone member, 12 to 21 feet thick. Thin-bedded magnesian limestones with a sparse fauna. *Pentamerus oblongus*, *Cælospira plicatula*, *Hyattidina congesta*.

Basal shale, 2.5 to 6 feet thick. Green to grayish shales, with *Cælospira hemispherica* and *C. plicatula*. Rests abruptly on the Medina. This zone is often correlated with the Sodus member at Rochester, but there is nothing of value to support this reference.

Disconformity. Contacts sharp between adjacent formations. Sodus shale absent.

Medina formation. Thickness about 65 feet.

Thorold member. Massive, greenish white, cross-bedded sandstone, 8 feet thick. The "gray band" of Eaton.

Red and greenish gray, much cross-bedded and channeled sandstone, with very little shale, about 15 feet thick. *Arthropycus alleghaniense* and *Lingula cuneata* occur 2 feet beneath the top.

Thin-bedded red sandstones, with considerable red shales, and two or more zones of localized storm-rolled mud balls (concretions of authors), 35 to 40 feet thick.

Gray sandstone with green shale partings, 5 feet thick. Poor Medina fossils here, noted by Hall in 1838.

Cataract formation. Thickness about 54 feet. Seen best on each side of the small tunnel and in Evan's gully, on N. Y. C. R. R.

Upper dark green shales, 5 feet.

Thin-bedded green sandstone at top, followed by yellowish magnesian and argillaceous limestone, with small black shale pebbles, 5 feet, abounding in *Helopora fragilis*, fragments of *Lingula*, *Camærotæchia neglecta*, *Isochilina cylindrica*, and small gastropods.

Middle green shales, 10 feet.

Dark green shales, with very thin-bedded argillaceous magnesian limestones, 5 feet. *Helopora fragilis* common, *Lingula* in fragments, *Camærotæchia neglecta*, and *Whitfieldella*.

Lower dark green fissile shales, 7 feet.

Whirlpool sandstone member (Grabau, 1909), 22 feet thick. Heavy-bedded, clean, white, somewhat coarse, cross-bedded sandstone. Thin-bedded in upper 5 feet. No fossils seen in the gorge exposures. See plate 13, figure 1.

Disconformity. Base of Siluric. The slightly undulatory contact with the Queenston is well shown along the Grand Gorge trolley line.

Queenston (Grabau). Top of Ordovician (Richmondian). Exposed for 115 feet. Thickness in deep wells 1,085 feet. Brick-red sandy shales with oxidized green streaks. No fossils.

Thorold, Ontario, section (10 miles west of Niagara Gorge).—Reconstructed from Logan, *Geology of Canada*, 1863, pages 313, 322-323.

Lockport dolomite. Present about 33 feet.

Eroded unconformity as at Niagara Gorge.

Rochester shale. Thickness about 71 feet.

Dark bluish bituminous limestone, often rich in Rochester fossils. Thickness 8 feet. Many corals, *Stephanocrinus angulatus*, *Eucalyptocrinus decorus*, *Caryocrinus ornatus*, etc.

Bluish gray cement rock. Thickness 8 feet.

Bluish black shales, with thin bands of impure limestone having *Dalmanites limulus*. Thickness 55 feet.

Clinton formation. Thickness 26 feet.

Irondequoit limestone member. Gray, coarse-grained, subcrystalline limestone, with iron and copper pyrites. Thickness 10 feet. *Rhynchotretra cuneata*, *Whitfieldella cylindrica*.

Wolcott limestone member. Bluish gray magnesian limestones with shale partings. Thickness 10 feet. Common near base, *Pentamerus oblongus* and *Stricklandinia canadensis*. According to Logan these two members thicken to the west.

Bluish drab argillaceous limestone, a cement rock. Thickness 3 feet.

Bluish gray limestone with much iron pyrite. Thickness nearly 3 feet.

Disconformity.

Medina formation. Thickness exposed 14 feet.

Bluish green argillaceous shale, with *Arthropycus alleghaniense*. Thickness 4 feet.

Thorold member or "gray band." A white fine-grained sandstone. Thickness 10 feet.

Grimsby, Ontario, section (20 miles west of Thorold).—In cuesta along both sides of Forty Mile Creek, back of the "Village Inn" (see Parks, *Guide Book No. 4*, Twelfth International Geological Congress, 1913, pages 130-136).

Lockport dolomite. Present 12 to 25 feet.

Gasport limestone member. A thick-bedded crinoidal limestone with a fauna that is essentially Rochester in character (*Atrypa nodostrata*, *Rhynchotretra americana*, *Spirifer crispus*, *S. radiatus*, *Whitfieldella nitida*, many Bryozoa, etc.), but it also has *Spirifer eudora* and *Eucalyptocrinus tuberculatus*.

DeCew member. The basal thin-bedded, impure, undulatory limestone (cement rock) has a thickness of 8 feet. At the head of the falls and in the cliffs above, the contacts with the Rochester and the Lockport are well shown. The upper contact is seen to have decided undulations with the pyritiferous layer at the base of the Gasport limestone. The higher beds are harder than those of the DeCew, and therefore make projecting cliffs.

Disconformity. Contact between adjacent beds easily found, but the lithic difference not marked. Time break short, with about 20 feet of the Rochester lost through erosion.

Rochester shale. Thickness about 39 feet.

Dark blue shale beds that become more and more fossiliferous and softer downward. The greatest abundance of fossils is in the lower 15 feet, in which may be noted *Caryocrinus ornatus*, *Stephanocrinus angulatus*, *Ichthyocrinus levis*, *Eucalyptocrinus celatus*, *Orthis flabelites*, *Spirifer niagarensis*, *Dalmanites limulurus*, *Lichas boltoni*, many Bryozoa, etc. (See Parks, pages 131-133, for more complete fauna.)

Clinton limestone. Thickness 14 feet.

Irondequoit limestone in one bed 4 feet thick. Hard, crystalline, pinkish, crinoidal limestone, with zones of stylolites. There is no break between this bed and the Rochester, as the fauna continues largely from one to the other.

Wolcott limestone member. Thin-bedded magnesian limestones, with green shale partings, 10 feet thick. At 18 inches above the base *Pentamerus oblongus* is common and more rarely *Stricklandinia canadensis* and *Dinobolus conradi*.

The base of the Clinton is somewhat irregular in form and pyritiferous. One inch of shale separates it from the Medina.

Disconformity. Contact sharp between adjacent beds.

Medina formation. Thickness about 25 feet.

Dædalus archimedes bed at the top 18 inches thick. Locally the entire bed is made up of these lamellar and spiral burrows. On the under side of this bed occurs *Arthropycus alleghaniense*. In other places are seen regularly bedded gray sandstones ("gray band") with thin green shale partings through a thickness of 6 feet. This is the chief horizon of *A. alleghaniense*. Then a red sandy shale zone, barren of fossils, for 3 to 4 feet, below which are about 15 feet of thick-bedded, somewhat cross-bedded, gray and red mottled sandstones.

Cataract formation. Thickness about 80 feet. Not well exposed. For fauna see Parks, pages 135-136.

The *Whirlpool* heavy-bedded basal sandstone is here 6 feet thick. The basal 4 inches has much pyrite and green shale pebbles derived from the Queenston. The sandstone also fills sun-cracks in the red shales below.

Disconformity. Base of Siluric.

Queenston brick-red shales, exposed for over 100 feet. Top of Ordovician (Richmondian).

Stony Creek, Ontario, section (10 miles west of Grimsby).—On cuesta in gulch directly back of village. The Canadian Pacific Railway crosses over the mouth of the gulch. This is the finest single exposure along the entire cuesta in Ontario, but above the Cataract is difficult of access.

Lockport dolomite. Present about 32 feet.

At the top are seen thin-bedded, chert-bearing, gray dolomites with a thickness of about 12 feet. Below this are about 20 feet more of gray dolomites with far fewer chert nodules. The base of the Lockport is decidedly sandy and pyritiferous and the weathering away of this zone easily distinguishes the contact with the Rochester.

Disconformity. Contact sharp between adjacent beds. About 40 feet of Rochester is absent.

Rochester shale. Thickness about 25 feet.

Hard dark blue shales alternating with thin limestone bands, many of which are replete with bryozoans and some brachiopods. The contact with the Clinton is also sharp, but no break in sedimentation is recorded.

Clinton limestone. Thickness about 14 feet.

Irondequoit limestone member, in a single bed 4.5 feet thick.

Wolcott limestone member. The thin-bedded Clinton in sharp contact with the Medina below. Thickness about 9 feet. The basal 2 to 8 inches of the Clinton is a clean-washed sandstone with occasional small pebbles of a greenish sandstone, both derived from the Medina. As usual, 18 inches above the base *Pentamerus oblongus* (Clinton form) is common.

Disconformity. The evenly bedded Clinton limestone on the decidedly cross-bedded sandstones of the Medina makes a sharp and broken contact.

Medina sandstone. Thickness about 18 feet.

Light green, thin-bedded, decidedly cross-bedded, clean-washed sandstones, with a thickness of about 7 feet.

Variegated, green and red, thin-bedded sandstones, with a thickness of about 10 feet. Near the middle of this zone occur mud-ball formations (sea-churning) like those seen in the Medina of the Niagara Falls Gorge.

Light green sandstone and shale in thin alternating beds with a total thickness of about 1 foot (basal sandstone 1.5, shale 2, sandstone 2, and shale and thin sandstones 4 inches). Marked by an abundance of *Scolithus verticalis* burrows. On the under side of the lowest sandstone occur rarely *Helopora* and undescribed bivalves, forms that also occur below in the Cataract.

Cataract formation. Thickness about 90 feet. Exposure complete.

Cabots Head shale member. Upper red and green sandy shales with bands of impure magnesian limestones having a thickness of about 22 feet. Toward the top the formation becomes more and more sandy and in the uppermost 5 feet has intraformational conglomerates, the pebbles of which are small. At 3 to 5 feet below the Medina occur abundantly *Helopora fragilis*, *Lingula clintoni* and undescribed bivalves. These occurrences prove that there is no break here between the Cataract and the Medina.

Lower olive green shales (decidedly so in upper half) with many thin layers of magnesian limestone that become more abundant downward and are replete with fossils. Total thickness 48 feet. *Rhinopora verrucosa* and *Calospira planoconvexa* appear 10 feet above the Whirlpool sandstone. Twenty-five feet higher occurs an abundance of large *Whitfieldella* near *oblata*.

Manitoulin limestone member. Basal magnesian limestones, 8 feet thick.

Whirlpool sandstone member, 12 feet thick. The upper 3 feet or more are thin-bedded, greenish, shaly sandstones, more or less cross-bedded. Below, the sandstone is regularly and heavy bedded, greenish white in color, and may or may not be blotched with red. The basal 1 or 2

inches has green weathered shale pebbles of the lower red Queenston, and there is here also much iron pyrite. The under side of the Whirlpool fills into the sun-cracked (the cracks are sometimes 2.5 inches deep), but otherwise almost even surface of the Queenston.

Disconformity. Base of Siluric. See contact in plate 13, figure 2.

Queenston brick-red shales barren of organisms. Top of Ordovician (Richmondian).

Hamilton, Ontario, section (6 miles west of Stony Creek).—On cuesta back of the city between the two inclined planes. See Logan, *Geology of Canada*, 1863, pages 310-334; Spencer, *Canadian Naturalist*, vol. 10, 1883, page 8; and Parks, *Guide Book No. 4*, Twelfth International Geological Congress, 1913, pages 136-139.

Lockport dolomite. Present about 37 feet. The base of the formation is best studied at the head of John street beside the road up the "mountain." At the very base here occurs an iron-pyrite fine-grained sandstone up to 3 inches thick. This is followed by a dolomite 2 to 4 inches thick, slightly sandy, pyritiferous, and with shale pebbles up to 1 inch in diameter, derived from the Rochester below. Higher there usually occurs a thin irregular shale (in layers or pockets up to 4 inches thick) of reworked Rochester, indicating that this formation had not yet been covered everywhere. Over these overlapping basal deposits follows the regular thin-bedded, cavernous, dark Lockport dolomite, but here devoid of chert nodules through a thickness of 5 feet. In the next higher 18 inches there are some of these diagenetic nodules, followed by light gray, thin-bedded, fine-grained dolomite that becomes more and more replete with nodules (many containing *Astylotrongia præmorsa* and *Aulocopina granti*) and chert stringers. (For a more complete faunal list see Parks, 1913: 137.) The great majority of the graptolites (*Dictyonemoid*) described by Bassler are from these chert beds.

Disconformity. Contact sharp between adjacent beds. The break in sedimentation is here clearly made out, as the greater part of the Rochester is absent.

Rochester formation. Thickness about 15 feet.

The greater part of the upper Rochester is absent.

A series of dark green, somewhat calcareous, limy shales, interbedded with thin bands of fine-grained magnesian limestones (the "blue building stone"). Fossils are practically absent in the upper 6 feet, followed by a zone a few inches thick replete with Trepostomata Bryozoa, more rarely *Fenestella*, *Dictyonema*, *Meristina*, and *Rhynchotrete americana*. The most abundant fossils throughout this zone are crinoidal ossicles, and none of the Rochester guide fossils are present.

The contact with the Clinton is sharp, but the fauna indicates no time break. At the very base of the Rochester there is a shale zone 1 inch thick, followed by a Clinton-like limestone 2 inches thick, with *Atrypa reticularis*. Another shale zone, several inches thick, follows, and is succeeded by a thin bed of magnesian limestone more like

those higher in the formation. Both of these limestones have small shale pebbles, and as these latter do not come from the Clinton, they are regarded as of intraformational origin.

Clinton limestone. Contact sharp with Rochester. Thickness about 15 feet. Seen best at head of Wentworth Street incline.

Irondequoit limestone member. One bed of hard, cavernous, crystalline, slightly pinkish, crinoidal limestone. Thickness 4 feet 5 inches.

Wolcott limestone member. Seven beds of gray magnesian limestones with shale partings. Thickness (16, 18, 16, 18, 18, 10, 8 inches) 8 feet 8 inches.

Basal thin-bedded, gray, magnesian limestone, 18 inches thick. At the base it is sandy, glauconitic, and pyritiferous for about 2 inches, then the sand is less abundant, but the glauconite and pyrite continue into the limestone; near the top is an abundance of *Pentamerus oblongus* (Clinton form).

The sharp contact with the Medina, the very different sediments, and the marked faunal difference indicate that the Clinton-Medina contact is here broken.

Disconformity. Contact sharp between adjacent beds.

Medina sandstone. Thickness about 12 feet. Seen to best advantage at the head of John street beneath the large road-metal quarry between two stone crushers and back of the covered reservoir building.

At the top about 4 feet of thin-bedded light green sandstones, interbedded with sandy shale. Below, a horizon 4 to 6 feet thick of heavy-bedded sandstones, with localized zones of large (2 feet deep) mud-ball (sea-churning) formation. Next lower occur 4 to 6 feet of thin-bedded sandstones, alternating with shales, the basal bed of 1 foot thickness having in abundance *Lingula clintoni*, a form also found in the Cataract below. The contact between the Cataract and the Medina is, however, a sharp one, as may be seen in plate 14, figure 1.

Cataract formation. Thickness about 90 feet. Seen to best advantage beneath and to the south of the Wentworth Street incline and along the Jolly Cut road. Contact with Medina above is sharp, Cataract green shale below and gray sandstones above. There appears, however, to be no break in sedimentation here.

Cabots Head shale member. Green shales at the top variable in thickness from 6 to 18 inches. These then change below into red shales, and at about 5 feet beneath the top abound in *Phænopora* and other Bryozoa.

Red argillaceous and sandy beds, 6 feet thick, abounding in *Helopora*.

Red shales with an occasional sandy magnesian limestone, 10 feet seen.

All of the above beds especially rich in bryozoans.

Covered area. Thickness about 30 feet.

The rest of the Cataract occurs in the Mills and Webb quarry.

Manitoulin member. Thin-bedded, green and reddish, magnesian limestone, with much interbedded shale, 20 feet thick. Abounds in *Helopora* and other fossils.

Sandstone layer, 4 inches thick.

Thin-bedded magnesian limestones, without shale partings, 8 feet thick.

Fossils are common, among them *Helopora*, *Favosites*, and *Plectambonites transversalis*.

A dolomite bed 12 to 16 inches thick.

Sandy shale zone 2 to 10 inches thick.

Whirlpool sandstone member. Basal greenish gray sandstone in one bed 10 feet thick.

Disconformity. Base of Siluric.

Queenston. Brick-red sandy shales. Exposed for about 250 feet. No fossils. Top of Ordovician (Richmondian).

Dundas, Ontario, section (5 miles northwest of Hamilton).—On cuesta and gulch back of the town about one mile in and around the large quarries. See Logan, *Geology of Canada*, 1863, pages 313-314 and 325-326; and Spencer, *Canadian Naturalist*, vol. 10, 1883, pages 6-7.

Lockport dolomite. Present 37 to 169 feet. The contact with the Rochester is not easy to make out here. The basal few inches of the Lockport, however, have a conglomerate of shale pebbles, but there is far less of sand and pyrite than at Hamilton. The Lockport at this place begins with the Gasport crinoidal magnesian limestone.

Disconformity. Nearly all of the Rochester is absent.

Rochester formation. Thickness about 6 to 7 feet. Seen to best advantage at the waterfall in the steep gulch. Here these dark calcareo-arenaceous shales are hard to distinguish from the overlying Lockport, but elsewhere under the influence of weathering they break up into shaly material, as the Lockport never does. Fossils scarce. Billings reports *Rhynchonella (?) robusta*, *Spirifer radiatus*, *Meristina naviformis*, *Atrypa reticularis*, etc.

Clinton limestone. Contact sharp with Rochester. Thickness about 14 feet. This formation has here about the same characters as at Hamilton. The Irondequoit member has a thickness of 5.5 feet and the Wolcott member of about 8.5 feet. The basal layer of the Clinton is replete with glauconite and there is also much sand in the dolomite. Eighteen inches above the base occurs an abundance of *Pentamerus oblongus* (Clinton form), and 6 inches higher occur *Favosites niagarensis* and *F. favosus*.

Disconformity. Contact sharp between adjacent beds. Section broken here.

Medina sandstone. Thickness apparently not over 8 feet. At the top are evenly bedded thin sandstones for about 5 feet, then green shales with some sandstones, and at the base 2 feet of sandstones. No mud-ball formation seen here. Contact with the Cataract below also sharp.

Cataract formation. Thickness about 94 feet (Logan).

Cabots Head shale member. Green shales with interbedded thin magnesian limestones, 6 feet.

[The rest of the section is taken from Logan.]

Red ferruginous shale and shaly limestones, 7 feet.

Red, ferruginous, impure, thin-bedded limestones, abounding in fossils, 7 feet thick. *Helopora fragilis*, *Rhinopora verrucosa*, *Phanopora explanata*, *Leptæna rhomboidalis*, *Camarotoechia neglecta*, *Pterinea (?) primigenia*.

Red marly shale (4 feet), green shale (2), and red, calcareous, thin-bedded sandstones (1). Thickness 7 feet.

Green and gray, impure, calcareous shale, with the same fossils as above. Thickness about 11 feet.

Bluish gray calcareo-arenaceous shale, 11 feet.

Concealed area, 7 feet.

Buff shales, with thin beds of fossiliferous magnesian limestone, 12 feet. *Helopora fragilis*, *Rhinopora verrucosa*, *Platystrophia biforata*, *Leptæna rhomboidalis*, *Cælospira planoconvexa*.

Bluish gray and green shales, with thin bed of magnesian fossiliferous limestone, 8 feet. Fossils same as those below.

Manitoulin member. Dark bluish gray magnesian limestones and shale weathering a pale red, 7 feet. The most fossiliferous horizon and the type locality for *Cælospira planoconvexa*. Also here *Helopora fragilis*, *Pachydictya crassa*, *Phænopora ensiformis*, *Rhinopora verrucosa*, *Rhipidomella circulus*, *Orthis flabellites*, *Hebertella fausta*, *Leptæna rhomboidalis*, *Platystrophia biforata*, *Atrypa rugosa*, *Whitfieldella naviformis* (this identification very doubtful), *Cornulites distans*, *Modiolopsis* (?) *orthonota*, *Encrinurus cf. punctatus*, etc.

Gray, compact, calcareous sandstone in two beds, 21 inches thick. *Zaphrentis*, *Helopora fragilis*, *Pachydictya crassa*, *Phænopora ensiformis*, *Leptæna rhomboidalis*, *Dalmanella elegantula*, *Camarotachia neglecta*, *Cælospira planoconvexa*, and *Cornulites distans*.

Gray, thin-bedded, shaly sandstones with greenish shale partings, *Cælospira planoconvexa*, *Modiolopsis* (?) *orthonota*.

Whirlpool sandstone member. Basal gray, heavy-bedded sandstones, 8.5 feet thick.

Disconformity. Base of Siluric.

Queenston. Top of Ordovician (Richmondian). According to the Dundas artesian well the thickness is estimated at 535 feet.

Limehouse, Ontario, section (25 miles north of Dundas).—On cuesta cut by Grand Trunk Railway, 3 miles west of Georgetown, Ontario.

Lockport bluish gray, heavy-bedded, cavernous dolomite, with much fragmental organic material. Quarried for lime burning. Thickness present 20 feet. The lowest 2 to 4 inches consists of a basal conglomerate made up of small and weathered (yellow) Clinton limestone pebbles in a muddy dolomite. The regular Lockport dolomite appears at about 6 inches above the Clinton. In the basal beds occur many heads and tails of a large *Illænus* (near *I. toxus*) piled upon one another like saucers. Also *Halysites* with large corallites in loose chains.

Disconformity. No Rochester here. Contact sharp between adjacent beds. [Grabau as censor holds that all of the Rochester here and elsewhere is changed in character to that of the Lockport, and therefore that there is no break. Likewise for the next disconformity, where all of the Medina is said to be changed into the Cataract facies. The writer does not subscribe to these conclusions.]

Clinton thin-bedded, gray to greenish (weathering yellowish to white), and more or less impure limestone (sometimes called a water-lime, but not used for lime). Thickness 6.5 feet.

Disconformity. No Medina sandstone here. Contact sharp between adjacent beds.

Cataract formation. Thickness exposed 18 feet.

Cabots Head shale member. Upper green shales with very thin bands of magnesian limestone abounding in *Helopora* to within 18 inches of top; 7 feet thick.

Red shales dominated by ferruginous (almost an iron-ore), more or less magnesian limestones, 6 feet thick. Replete with many species of bifoliate and Trepostomata Bryozoa typical of upper Cataract. Also here *Leptæna rhomboidalis*, *Camarotoechia neglecta*, and small hemispheric masses of *Favosites*.

Red shales, with some thin bands of green shales down to railway; 5 feet seen. *Helopora* are also common, but the bryozoans of the higher beds are practically absent.

The remainder of the Cataract is not exposed here. At Kelso, 13 miles southwest, the formation has a thickness, according to Williams, of 92 feet.

Glenwilliam, Ontario, section (5 miles north of Limehouse).—On the lower part of cuesta.

Cataract formation. Lowest part only exposed.

Manitoulin member. Magnesian thin-bedded limestones, more sandy and shaly than usual. Fossils are also less abundant. *Clathrodictyon vesiculosum*, *Favosites venustus*, *Heliolites interstinctus*, *Halysites microporus*, *Zaphrentis bilateralis*, *Rhinopora verrucosa*, *Rhipidomella circulus*, *Leptæna rhomboidalis*, *Atrypa rugosa*, *Calymene*, *Encrinurus*.

Whirlpool member. Basal gray sandstone, 12 feet thick. The lowest 2 to 4 inches abound in pyrite, and the sands fit into the sun-crackings of the Queenston below. The lower 9 feet regularly bedded and making a good building stone much used in Toronto. In color it is usually gray, but in places is blotched with red or passes entirely into a light red color. The upper 3 feet are much cross-bedded and contain many *Modiolopsis* (?) *orthonota* and an abundance of "fucoid" markings and vertical "worm burrows" (the shape of cup corals).

Disconformity. Base of Siluric.

Queenston brick-red shales, much used here for pottery, drain pipes, and brick. Top of Ordovician (Richmondian).

Cataract, Ontario, section (13 miles north of Limehouse and 48 miles northwest of Toronto).—Cuesta along Forks of Credit. Type section of Cataract formation along the valley of the Credit and about the cataract. See Parks, Guide Book No. 5, Twelfth International Geological Congress, 1913, pages 8-13.

Lockport dolomite. Heavy-bedded, cavernous, light gray dolomite seen on the railway to Elora at the spring near Cataract Junction. Thickness present 30 feet.

Disconformity. No Rochester or Clinton here.

Cataract formation. About 106 feet thick.

Cabots Head member. Upper green shales with very thin magnesian limestones, about 20 feet thick. *Helopora fragilis* is common in the limestones. At Limehouse this zone is only 6 feet thick.

Red, decidedly ferruginous, shaly limestone, with thin shale zones, 5 feet. *Helopora fragilis* very common here. Other Bryozoa also occur, but not so abundantly as at Limehouse or Dundas.

Middle green shales, with occasional thin magnesian limestones, that become more abundant downward; about 40 feet thick. In the shales fossils are scarce, but in the limestones *Helopora* (two or more species) are exceedingly common. Also here *Orthis flabellites* and other forms of the Manitoulin member.

Manitoulin member. Greenish magnesian limestones in beds up to 12 inches thick, with irregular zones of chert, separated by thin bands of green shale, about 25 feet. The transition zone to the Whirlpool consists of not over 3 inches of shale. The main horizon for Cataract fossils. At 8 feet above the base, a thin shale abounds in many small fossils, *Whitfieldella* n. sp., *W. cf. oblata*, *Atrypa rugosa*, *A. n. sp.* *Calospira planoconvexa* is common between 8 and 15 feet above the base.

Whirlpool member. Basal heavy-bedded, rippled and decidedly cross-bedded, white, or mottled with red spots, or pinkish, fine-grained sandstones, 16.5 feet thick. Much quarried for building stone all along the Credit. At the top occurs *Modiolopsis* (?) *orthonota*.

Disconformity. Base of Siluric.

Queenston. Top of Ordovician (Richmondian). Brick-red sandy shales. Exposed about 250 feet.

Collingwood, Ontario, section (48 miles northwest of Cataract).—Five miles to the south of Collingwood rises the high cuesta, "Blue Mountain," the top of which is fully 800 feet above Georgian Bay. The section is toward the top of the mountain.

Lockport dolomite making vertical cliffs at the top of the mountain. Thickness present 160 feet (Logan).

Disconformity. All Rochester and Clinton absent.

Cataract formation. Thickness about 32 feet.

Cabots Head shale member covered and replete with springs. Thickness estimated at 20 feet. Loose magnesian limestones along the roadside abound in bryozoans. The top is in all probability eroded away.

Manitoulin member. Thin-bedded, light blue, finely granular, magnesian limestones, without shale partings. At crest of mountain road. Thickness 12 feet, but near Meaford (20 miles to the northwest) attains 29 feet (S. E. Whittaker). Fossils scarce except *Leptæna rhomboidalis*.

Whirlpool member not present here. Last seen at Glen Huron, 12 miles south of Collingwood (Williams).

Disconformity. Base of Siluric.

Queenston. Top of Ordovician. Brick-red sandy shales devoid of fossils, about 45 feet thick.

Richmondian. Green sandy shales with thin zones of magnesian limestones having minute Bryozoa, Ostracoda, *Zygospira recurvirostris* and *Leperditia* cf. *cæcigena*. Thickness about 90 feet.

A thick series of light blue, somewhat calcareous shales. At the top thin zones of limestone occur rarely, but increase in quantity more and more downward, and in the same way occurs a greater abundance of characteristic Richmondian fossils. From the dominantly calcareous strata in the lower part of the section, with many fossils, one rises higher into more and more shaly and then sandy strata, the corals and brachiopods drop out, the bryozoans continue, but the Trepostomata finally also drop out, leaving only the minute forms to attain the top of the green shales. Thickness up to Queenston not clearly made out, but apparently not less than 340 feet. Some of the Richmondian fossils are *Tetradium fibratum* (rare), *Streptelasma rusticum* (rare), *Hebertella insculpta* (common), *Ambonychia radiata*, *Modiolopsis concentrica*, and *Whiteavesia pholadiformis*.

Owen Sound, Ontario, section (38 miles west of Collingwood).

Lockport limestone well exposed in West Owen Sound. Heavy-bedded, fine-grained, light gray, fossiliferous dolomite, at least 70 feet thick. "White rock" of quarrymen.

Disconformity. Actual contact not seen.

Cataract formation. About 130 feet (thickness determined by Williams).

Cabots Head member. Covered zone of shale, with red zones and ferruginous bands. Thickness estimated at 50 feet.

Blue-green shales with thin-bedded, nodular, and even-bedded limestones replete with Cataract fossils. Thickness 25 feet. Seen at Wright's flour mill in West Owen Sound.

Manitoulin limestone member, 30 feet thick. Thin-bedded, light blue ("blue rock" of quarrymen) to gray, finely granular, magnesian limestones, with thin zones of chert. Quarried for lime to the east of Owen Sound. In the upper 10 feet the chert zones abound in fine fossils, among them *Rhinopora verrucosa*, *Platystrophia biforata*, *Orthis flabellites*, *Dalmanella elegantula*, *Schuchertella subplana*, *Lepetana rhomboidalis*, and *Calospira planoconvexa* (exceedingly common here).

Disconformity. Base of Siluric.

Queenston formation. Top of Ordovician (Richmondian). Brick-red, soft, sandy shales, with very thin sandstones in the upper 8 feet; about 50 feet. No fossils. In places near the top occur zones of sun-cracking with the prisms small. Thirty feet beneath the top occur lumps of secondary impure gypsum. Forty feet from the Cataract in a thin green shale occur *Hebertella sinuata*, Richmondian Bryozoa, *Leperditia* cf. *cæcigena*, and other Ostracoda.

Cabots Head, Bruce Peninsula, Ontario, section (53 miles northwest of Owen Sound).—Information from Dr. M. Y. Williams. Also see Logan, *Geology of Canada*, 1863, pages 319-320.

Lockport dolomite. Massive cliff-making. Present 165 feet (Logan).

Disconformity.

Cataract formation. Thickness 60 feet.

Cabots Head member. Top probably eroded away. Soft gray shale locally tinged with red, 4 feet.

Thin-bedded limestones with branching *Favosites* and *Helopora fragilis*, 5 feet.

Hard green argillaceous shale, 36 feet.

Manitoulin member. Massive dolomite, 15 feet.

Disconformity. Base of Siluric. This contact is illustrated in plate 14, figure 2.

Queenston. Top of Ordovician (Richmondian). Hard and soft red shales, about 45 feet, down to level of Lake Huron. The last place to the north that these red shales are seen, for on the Manitoulin all of the strata beneath the Cataract are calcareous normal marine deposits and have an abundance of Richmondian fossils.

Manitowaning, Manitoulin Island, Ontario, section (45 miles north-west of Cabots Head).—Seen by the writer in 1912 under the guidance of M. Y. Williams. See Williams, Guide Book No. 5, Twelfth International Geological Congress, 1913, pages 89-97.

Lockport dolomite. Actual thickness as measured by Williams 240 feet (Bell's 450 feet was calculated from the dip).

Disconformity.

Cataract formation. (Clinton of Bell.) Thickness averaging 100 feet.

Cabots Head member. Usually a covered zone of friable red clay (red marl of Bell), almost barren of fossils, from 27 to 66 feet thick. At the top the shales are nearly always oxidized into green shale by percolating waters.

Manitoulin member, 50 to 60 feet thick. Thin-bedded, gray to yellowish, fine-grained, magnesian limestones to massive dolomites, without shale partings. In the upper 20 feet there are many small reefs of Bryozoa, Stromatopora, and corals. Fossils as pseudomorphs. *Clathrodictyon vesiculosum*, *Halysites microporus*, *Heliolites*, *Favosites venustus*, *Diphyphyllum venosum*, *Acervularia* (?) *gracilis*, *Pachydictya crassa*, *Platystrophia bifurcata*, *Orthis flabellites*, *Hebertella* cf. *daytonensis*, *Dalmanella elegantula*, *Rhipidomella hybrida*, *Schuchertella subplana*, *Camarotoechia neglecta*, *Atrypa* n. sp., *Caelospira planoconvexa*, *Whitfieldella*, *Cyclonema cancellatum*, etc.

Disconformity. Queenston red shales absent and transformed into the

Richmondian formation. The best exposures are at Clay cliff on the eastern end of the island, where good fossils are plentiful in a Richmondian section at least 160 feet thick. Beneath are about 100 feet of Lorraine, and 130 feet of Eden. Deep wells give the thickness of the entire Cincinnati deposits as not less than 435 feet.

East of Manitowaning 1.5 miles may be seen along the roadside a good exposure of the uppermost Richmondian in contact with the Cataract sandy limestone. Below these Siluric beds are 12 feet of greenish clays without fossils, followed by a series of thin-bedded, sandy and shaly, magnesian limestones, 15 feet thick, with many Bryozoa throughout, other fossils being almost absent.

CLOSE OF THE CRETACEOUS AND OPENING OF EOCENE
TIME IN NORTH AMERICA ¹

BY HENRY FAIRFIELD OSBORN

(Presented before the Paleontological Society December 31, 1913)

In introducing this symposium on a critical point in geologic time emphasis must first be laid on the fact that the *Periods* were defined during the last century by European paleontologists, and that American events can be dated only by comparison of American with European faunas and floras, unless simultaneous and world-wide diastrophic movements can be demonstrated to have occurred.

The demarcation between the Cretaceous and the Eocene periods of Europe rested first on the work of Deshayes on the extinct molluscan fauna of the Paris basin. It gradually developed in definition and clearness under Lyell, D'Orbigny, Mayer, and Eymar. Gradually also vertebrate reptiles and mammals entered into the problem, and the formations along the northern coast of Europe and Belgium, with their contained marine fossils, served to define the *Maastrichtien* stage (Dumont, 1849), while in the north another late Cretaceous phase typified the *Danien* stage (Desor, 1846). According to Haug (1912), the *Danien* overlies the *Maastrichtien* concordantly, and thus closes the Cretaceous period. The fauna is purely marine and exclusively Cretaceous. Some authors also place the overlying *Montien* in the Cretaceous.

The *Maastrichtien* as exposed in Belgium includes a rich reptilian fauna, which comprises several kinds of mosasaurs, great marine turtles, iguanodont dinosaurs, and their enemies, the carnivorous dinosaurs. This is our last view of the dinosaur life of Europe. The *Maastrichtien* fauna has not been closely correlated up to the present time with an American fauna. According to Williston, it is subsequent to any known American mosasaur fauna, and this author regards the *Maastrichtien* as a lower phase of the *Danien*. It is to be noted also that no late Cretaceous terres-

¹ Manuscript received by the Secretary of the Geological Society June 12, 1914.

This paper is an introduction to the symposium on this subject held at the Princeton meeting of the Society December 31, 1913, and January 1, 1914.

trial fauna is known in Europe corresponding with the *Danien* time epoch or with the "Lance" fauna of North America.

The very ancient Paleocene formations of northern Europe, including the problematic *Montien* epoch and the well defined *Thanétien* marine phase, are along the sea borders, and consequently are unfavorable to the preservation of mammalian life. They contain no dinosaurs or mosasaurs. Among these are the *Sables de Rilly*, seashore sands containing many marine mollusks which are similar to those in the *Sables de Bracheux*, another Paleocene formation. In France, however, as long ago as 1841, one fluviomarine formation yielded a single mammal, *Arctocyon primævus*, in beds correlated in time with the *Thanétien*. At a slightly subsequent period of *Thanétien* time a river-borne formation includes the celebrated mammalian fauna of Cernay and the single surviving Cretaceous reptilian type *Champsosaurus*.

Without exception it may be said that all the paleontologists of Europe have considered the Cretaceous as the period of the final extinction of the terrestrial dinosaurs and the marine mosasaurs; and they have similarly defined the Paleocene not only by its new forms of marine mollusca, but by the survival of the characteristic plagiaulacid mammals of the Mesozoic and the first general appearance of a primitive mammalian land fauna, which broadly corresponds with a similar Puerco-Torreon-Fort Union fauna in North America.

The discussion to which we are devoting this session of the Paleontological Society is of great interest and importance because a number of eminent American paleobotanists and geologists, as well as certain invertebrate paleontologists, are of the opinion that the close of Cretaceous time occurred long before the extinction of certain great families of terrestrial dinosaurs, and that as a consequence the opening of Eocene time is not the beginning of the so-called Age of Mammals, but embraces a prolonged closing chapter in the Age of Reptiles.

The various kinds of evidence which may be adduced in favor of this interpretation of the succession of phenomena in North America will be presented by Dr. F. H. Knowlton, who, firstly, will demonstrate that paleobotany does not indicate any sharp line of demarcation between the Upper Cretaceous ("Lance") and Lower Eocene, and, secondly, he will point out the evidence, which is accepted by a considerable number of American geologists, for the belief that there is widespread diastrophism occurring at a certain period long before the close of the Age of Reptiles. This diastrophic movement is believed by Doctor Knowlton to correspond with the close of Cretaceous and opening of Eocene time. It occurs long before the close of the Age of Reptiles.

The more traditional view that the sequence of life events was concurrent in America and Europe will be presented by the other speakers, who will contend that the Cretaceous terminates at the close of the Age of Reptiles and is marked by the extinction of the great terrestrial dinosaurs.

Dr. T. W. Stanton will consider the evidence of geology and invertebrate paleontology, and will endeavor to show that there is insufficient evidence of any general diastrophism prior to the close of the Age of Reptiles.

Mr. Barnum Brown will point out that the succession of Ceratopsian faunas in Upper Cretaceous time affords several distinct phases, the last of which is that of the so-called "Lance" formation, which alone contains the culminating genus *Triceratops*.

Dr. W. D. Matthew will compare the "Lance" and "Belly River" vertebrate faunas with those of the Paleocene of the Puerco and Torrejon, our oldest mammal-bearing horizons, and those of the *Thanétien* and *Cernaysien* beds of France and Belgium.

Dr. William J. Sinclair will describe the substitution of a rich mammalian for a terrestrial dinosaur fauna as it occurs in the succession of the Ojo Alamo (supposed Upper Cretaceous) and Puerco (supposed Paleocene) formations in northern New Mexico.²

² Doctor Sinclair's paper has been published as article xxii, vol. xxxiii, Bulletin American Museum of Natural History, 1914, pp. 297-316.

CRETACEOUS-TERTIARY BOUNDARY IN THE ROCKY
MOUNTAIN REGION ¹

BY F. H. KNOWLTON

(Presented before the Paleontological Society December 31, 1913)

CONTENTS

	Page
Introduction.....	325
Stratigraphic evidence.....	325
Paleobotanical evidence.....	331
Diastrophic evidence.....	334
The European time scale.....	335
Vertebrate evidence.....	337
Invertebrate evidence.....	339
Conclusions.....	340

INTRODUCTION

The thesis of this paper is as follows: It is proposed to show that the dinosaur-bearing beds known as "Ceratops beds," "Lance Creek beds," Lance formation, "Hell Creek beds," "Somber beds," "Lower Fort Union," Laramie of many writers, "Upper Laramie," Arapahoe, Denver, Dawson, and their equivalents, are above a major unconformity and are Tertiary rather than Cretaceous in age.

As this is essentially a stratigraphic problem and not, as some assume, an exclusively paleontologic one, a certain amount of structural data are necessary as a setting for the paleontology. It is proposed, therefore, first, briefly to present the evidence on which this unconformity is predicated.

STRATIGRAPHIC EVIDENCE

The geological formations here involved are spread widely over the States of New Mexico, Colorado, Wyoming, the Dakotas, Montana, and

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adjacent Canadian territory. It is held that the dinosaur-bearing beds above mentioned are separated from underlying beds by a major unconformity which makes the logical line of separation between Cretaceous and Tertiary.

In eastern Montana, eastern Wyoming, and the Dakotas, where far removed from the influence of the Rocky Mountain uplift, the formations involved are approximately horizontal. In a majority of cases within this area the dinosaur-bearing Lance formation appears to rest conformably on the underlying beds, and it is this condition apparently which has led many observers to deny the possibility of the existence at these points of a time interval of any importance. It needs but a moment's reflection, however, to show that because one formation lies in apparent conformity on another, this is not of necessity proof positive that the process of deposition continued uninterruptedly from the beginning of the first to the close of the second.

It may often happen that we must go outside the area where such apparent conformity obtains for the evidence which shall not only prove the existence of the stratigraphic break, but also the value of the hiatus. It happens, however, that even in the flat-lying beds in the Dakotas there is some evidence of the measure of this time interval. The maximum thickness of the Fox Hills—the formation beneath the Lance—is given as 450 feet, yet in many places it is 75 feet or less, and in exceptional cases appears to be entirely absent, and the Lance then rests on Pierre. An element of caution is necessary in interpreting this condition. Inequalities in the thickness of a formation of the well known character of the Fox Hills may be due to erosion or to irregularity of original deposition. That this unequal thickness in the Fox Hills is actually due to erosion and not to irregularity of deposition is indicated in at least two ways: First, by the finding of actual erosion surfaces, as, for instance, the one described by Calvert on Grand River, South Dakota, where within a horizontal distance of 500 feet there is an observed vertical cut of at least 72 feet, and other similar occurrences in western North and South Dakota and eastern Montana, and, second, by the difference in the invertebrate fauna in the lower and upper portions of the full Fox Hills section, which is approximately 1,000 feet in thickness. In the type section of Fox Hills at Fox Ridge, South Dakota, the beds show a thickness of only about 325 feet. The fauna in this type section is said to show more or less of a commingling of Pierre forms, and for this reason it was at one time the inclination to abandon the use of Fox Hills as a distinct formation and to regard it as merely a near-shore phase of the Pierre. Where the full 1,000-foot section of Fox Hills is present, as in the Denver

basin of Colorado, it appears, according to Dr. C. A. White, that the invertebrate fauna in the upper portion, while it contains some of the species of the lower portion, is on the whole distinct. This is taken to indicate that the full section of Fox Hills is nowhere present in the Dakotas, and that the incomplete development of the formation here is to be ascribed to removal of the upper part by erosion rather than to diminished rate of sedimentation or to stratigraphic overlap.

In Worthless Creek Valley, South Dakota, the pre-Lance unconformity is angular as well as erosional, the Fox Hills dipping north at an angle of 4 degrees, whereas the overlying Lance is horizontal. On the Moreau River, near Govert post-office, South Dakota, the Lance is horizontal, while the underlying beds dip northwest at an angle of 10 degrees. At a number of points in the eastern part of Custer County, Montana, the Lance rests on a distinctly eroded surface of the Fox Hills. Likewise, according to Barnum Brown, the same condition obtains on Hell Creek, in Dawson County, Montana.

Throughout much of Montana and Wyoming the conditions are the same as those above described, namely: The Lance is found resting on Fox Hills of different thicknesses, often with eroded surface, and in some cases, as at Forsyth, Columbus, etcetera, the Fox Hills is entirely absent and the Lance rests on Pierre and not always on its uppermost member.

It has been suggested that in those cases where the Lance rests directly on Pierre the lower sandstones of the Lance may be the fresh-water phase of the Fox Hills. Proof of this contention would be the finding of an area in which there is evidence either of a transition laterally from the purely marine conditions of the Fox Hills through brackish water to the suggested fresh-water facies of the "Lance," or a barrier separating two such areas of deposition on which neither facies was laid down. If the country within which the Lance is found resting on Pierre was one in which the stratigraphic relations were obscure on account of few or poor exposures, such transition or barrier might possibly have escaped detection; but on the contrary it is a region in which exposures are numerous and ample, and moreover is one in which investigation in recent years has been intensive, but no such condition has been observed.

In the cases thus far considered the discordance between the Lance and underlying beds is not always evident, nor is it always conspicuous when present, and hence it is held by some geologists to be of no more importance than unconformities acknowledged to be present at various horizons in the Lance. The essential difference lies in the fact that the unconformities within the Lance are obviously local and can be traced only for short distances, whereas the evidence in support of the pre-Lance

interval is cumulative, since it occurs at the same horizon throughout four great States. Of much greater significance, however, is the fact that this pre-Lance interval marks the boundary between the last of the underlying series of chiefly marine Cretaceous beds and the succeeding exclusively continental deposits which prevailed thereafter in the Rocky Mountain area. In other words, with a single exception this boundary marks the final retreat of the marine waters from the Rocky Mountain province.

The most complete measure of this pre-Lance unconformity is to be found in the vicinity of the mouth of the Medicine Bow River, in Carbon County, Wyoming. This unconformity was first detected and studied by A. C. Veatch in the vicinity of the town of Carbon, which is about 25 miles south of the Medicine Bow River. Veatch holds that this time interval represents the removal of more than 20,000 feet of strata. The horizon below this unconformity was called "Lower Laramie" by Veatch; but it is now regarded by the writer as the true Laramie, while the horizon above was called "Upper Laramie," now, in the writer's opinion, proved to be the dinosaur-bearing Lance formation, since it contains the remains of Triceratops. The line then recognized as the boundary between these two formations was structurally correlated northwest to the vicinity of the mouth of the Medicine Bow River, and thence up that stream for a distance of some 25 miles above its junction with the North Platte. According to Ball, at a point about 20 miles above the junction the "Upper Laramie" and "Lower Laramie" were found in contact with marked angular discordance.

During the present field season [1913] C. F. Bowen, of the United States Geological Survey, found remains of dinosaurs 1,000 feet or more below the horizon at which Veatch, in his reconnaissance work, had drawn the line between his "Lower Laramie" and "Upper Laramie." On account of the lithologic similarity of the rocks of this region, careful areal work may be necessary before the line can be drawn exactly. The line taken by Doctor Peale and the writer as that of the major unconformity may prove to be only one of the minor breaks known in the Lance, in which event Bowen's discovery merely reduces the supposed thickness of "Lower Laramie" rocks from 6,000 feet to 4,000 or 5,000 feet. On the other hand, indeed, it may be possible that dinosaurs actually occur in the "Lower Laramie,"² since they undoubtedly existed somewhere at this time, but none properly identified have as yet been found in undoubted Laramie.

² Since the above was written Bowen has informed me that the only dinosaur found in the lower part of the so-called "Lower Laramie" is about 700 feet above the top of the Lewis shale and 100 feet or more *below* a horizon containing Halymenites. This shows that probably it is not in the "Lower Laramie" at all, but in the Fox Hills unit, which in that area is mapped with the "Lower Laramie"!

Another fact of importance may be pointed out regarding this Medicine Bow region, namely: Bowen reports that he has found dinosaurs at a number of horizons that are from 300 to 500 feet above the top of the "Upper Laramie" as fixed by Veatch. This shows the extent of the vertical range of the dinosaur fauna.

In North Park, Colorado, the upper plant-bearing beds are apparently the same as those in Carbon County, Wyoming, as the two areas are closely connected, and from there it is but a step to the Denver basin of Colorado, where Whitman Cross demonstrated the presence of the great unconformity which separates the dinosaur-bearing Arapahoe and Denver formations above from the Laramie beneath. The Laramie is here reduced in thickness to about 1,600 feet, and at Colorado Springs, 75 miles south of Denver, which is the southernmost point at which Laramie is known, the thickness is reduced to 425 feet. W. T. Lee has shown to the satisfaction of many that the full Cretaceous section, to and including the Laramie, was laid down uninterruptedly over the area where the Rocky Mountains now exist. As the most complete section believed to represent the Laramie—namely, near Carbon, Wyoming—has a thickness of 5,000 feet, and as the Laramie in the Denver basin is only 425 to 1,600 feet thick, it is an indication that the unconformity may have removed at least 4,000 feet of beds and probably it was very much more; in fact Cross's estimates places it at 12,000 to 15,000 feet.

Between the Denver basin and Colorado Springs is a series of arkosic beds to which the name Dawson arkose has been given. The Dawson rests with marked discordance on all underlying beds, and is shown by its stratigraphic relations and contained flora to be the time equivalent of the Denver and Arapahoe formations. The Dawson contains abundant remains of dinosaurs, and in direct association with them Richardson found a mammal bone which Gidley pronounces to be characteristically Creodont, and says: "From our present knowledge the type represented could not be older than Wasatch." This association of dinosaurs and mammals is obviously of importance.

In the Raton Mesa region of southern Colorado and adjacent New Mexico, W. T. Lee has also demonstrated the presence of the same great unconformity, which by actual measurement has removed over 6,000 feet of beds and probably it was much more. Lee has also demonstrated the presence of the unconformity of many points around the southern end of the Rocky Mountains and up along the western base to southern Colorado. In this Raton Mesa region the beds above the unconformity, called the Raton formation, are not known to be dinosaur-bearing; but they do contain an ample flora, which is correlated with the Denver and

Dawson to the north, and to the south with the Eocene Wilcox formation of the Gulf region. The Wilcox formation is underlain by the marine Midway formation, at the base of which is the Tertiary-Cretaceous line of the Gulf coastal plain.

This post-Cretaceous hiatus has now been traced over a wide areal extent from the Canadian border to New Mexico, and it has been definitely tied in with a marine section in the Gulf region. It has been shown to occupy the same relative position throughout, and we are now in position to measure its magnitude. It appears to have involved at least the removal of the full thickness of Fox Hills and Laramie, where the maximum thickness of Fox Hills is 1,000 feet, and the thickest known section of Laramie is about 5,000 feet, or a total of 6,000 feet that may have been removed. It is not now known whether in Montana, eastern Wyoming, and the Dakotas the Laramie and the full Fox Hills section was ever deposited; but it seems certain to me that the pre-Lance hiatus is the time interval during which they were deposited in various areas and subsequently removed in whole or in part.

Suppose, for the sake of argument, we deny the validity of this unconformity as a criterion for establishing the Cretaceous-Tertiary boundary. Where, then, shall this line be placed? Take first the Lance formation. It is now established beyond question that the sedimentation was continuous and uninterrupted³ from the beginning of the Lance to and through the Fort Union. At the hundreds, even thousands, of localities where the two occur in the same section it has been found absolutely impossible to draw any satisfactory line between them on structural or lithologic evidence. The Lance is not mappable as distinct from the Fort Union. In one of the latest publications of the United States Geological Survey,⁴ which covers a very large area in eastern Montana, the two are mapped together, for, as W. R. Calvert, its author, says: "As a result of these conditions [outlined above] no attempt is made on the index map, or on the maps of the various areas treated in this report, to differentiate the Lance formation from the overlying strata described in connection with the Fort Union formation;" and he continues, "The lowest persistent lignite bed was in the field arbitrarily considered to be the upper limit of the Lance;" . . . and he concludes, "It cannot be emphasized too strongly that the upper limit adopted is merely suggestive, as the finding of *Triceratops* bones higher in the section will necessitate the upward extension of the formation." It would seem that a geological system ought at least to be a mappable unit!

³ Except possibly in the Cannonball region of North Dakota, which will be considered later, and within a single township in the Bighorn Basin of Wyoming.

⁴ Bull. 471, U. S. Geological Survey, 1912, p. 25.

The vertebrate paleontologists apparently would place the top of the Lance at the highest point at which dinosaurs have been found; but unfortunately in those areas—and there are very many of them—where no dinosaurs are known the Lance will be without a known top, and even where they do occur this sliding scale makes the fixing of the boundary dependent on the accident of discovery, and the point accepted as the line today may be very different from that necessitated by the work of tomorrow.

The invertebrate paleontologist would fix the top of the Lance by the highest point at which marine invertebrates have been found. This criterion is even more limited in its application than the last, since marine invertebrates are known from a comparatively small area in North and South Dakota.

It is obvious, therefore, that the fixing of this boundary has a practical aspect that must be considered, as well as the technical, stratigraphic, and paleontologic sides. If we subordinate the taxonomic significance of this pre-Lance datum plane as certain paleontologists would do, we substitute for it a criterion of vague, obscure, and unequal application. "Next to natural relationship the quality of convenience is the prime desideratum in stratigraphic taxonomy," says Ulrich in discussing the Ordovician-Silurian boundary; and he continues, "Let us, then, be reasonable and practical and accept with proper valuation these diastrophic boundaries, which nature has most clearly and widely indicated."

PALEOBOTANICAL EVIDENCE

I am possibly prejudiced when I say that to my mind the paleobotanical evidence is convincing and of the highest importance.

First, as to the evidence it affords regarding the distinctness of this time break: In the Raton Mesa region the Vermejo formation, the first beneath the unconformity, has a flora of 108 species. The Raton formation, the one next above the break, has a flora of 148 species. Only four species have been found in common. In the Denver basin the Laramie has a published flora of 97 species, six of which are found also in the Raton flora and 10 in the Arapahoe and Denver floras. In Carbon County, Wyoming, the "Lower Laramie" (true Laramie, in the writer's opinion) has a flora of about 50 species, five or six of which occur also in the dinosaur-bearing beds above, which has a flora of about 70 species. Throughout the vast area over which the Lance formation is known there have been reported 16 species of plants that come into its flora from beds below the unconformity—that is, from the Laramie, Montana, etcetera.

On eliminating the duplications in these several lists, as well as the

few forms now known to have been incorrectly identified, we have a total of only 21 or 22 species that are known to have crossed the line of the unconformity. The full significance of this small number is brought out when we aggregate the floras in the beds below and above the unconformity. In the lower beds—that is, Vermejo, Laramie, Montana, etcetera—there are 350 species, and in the upper beds—Raton, Dawson, Arapahoe, Denver, Lance, etcetera—there are over 700 species. Twenty-one or 22 species in common with 350 below and over 700 above is an insignificant number. It shows that more than 90 per cent of the Cretaceous flora was wiped out by the disturbances attending this diastrophic movement.

The length of this time interval is indicated by the flora in another way other than in the destruction of the species. If the flora in the beds above the unconformity was wholly or even largely of a different type from that in the beds below, it might mean that it had come in suddenly, “ready made,” from an adjacent area, without great lapse of time; but as a matter of fact it is in the main a continuation of the Cretaceous flora, and its evolution from the Cretaceous remnants implies a considerable length of time.

We may now consider the paleobotanical evidence regarding the correlation, age, etcetera, of the formations here involved, beginning with the area where our knowledge is most complete and passing over the ground in a reverse order from that in which the structural relations were discussed.

By common consent the physical break is made the basis of the separation between the Cretaceous and Tertiary in the Atlantic and Gulf coastal plain. In the Gulf region the Cretaceous Selma chalk and the Eocene Midway formation are on opposite sides of the line, and both are of marine origin. In a paper recently read before the Geological Society of Washington, Dr. L. W. Stephenson stated that the hiatus between the Cretaceous and Tertiary represented a longer time, regarded as due to evolutionary development, as measured by the change in life forms, than is indicated by the full Upper Cretaceous section of the region.

Above the Midway formation is the Wilcox formation, which is also marine except in the Mississippi embayment. The Wilcox contains a published flora of about 65 species, of which number about 25 are found also in the Raton formation. But Mr. E. W. Berry is engaged in the preparation of an elaborate monograph of the Wilcox flora, in which he will enumerate over 300 species, not one of which, by the way, has been found in the Cretaceous anywhere. Less than 80 of its species have been found outside of this formation. Between 30 and 40 species are now

known to be common to the Raton and Wilcox formations, and when Mr. Berry's work is available it will be found that there are probably not less than 50 common or closely related species. Mr. Berry is of the opinion that the Wilcox may be slightly younger than the Raton, and it may be that it is the equivalent of the upper part or perhaps the whole of the Midway, as well as a portion of the Wilcox.

This correlation of the Raton formation with the Wilcox and Midway is important, since it ties the Rocky Mountain section with the marine section of the Gulf, where the geologic relations are definitely known. This correlation was first pointed out by Lesquereux more than 40 years ago, when he had at his disposal only a handful of specimens from either area, and it is a pleasure to attest its correctness, which is not changed, with the fullest collections ever brought together for any Rocky Mountain area.

The Raton formation, as already indicated, contains a flora of 148 species, only four of which are known to occur in the Vermejo formation immediately below. This flora is especially characterized by vast numbers of palms, some with leaves 6 or 8 feet in diameter, and is rich in figs, cinnamons, magnolias, bread-fruit trees, etcetera, and indicates a moist, warm, possibly subtropical climate. The Raton formation is correlated by its flora, as well as by its stratigraphic relations, with the Denver formation of the Denver basin. The latter—the Denver—has a published flora of 98 species, over 40 per cent of which are common to the Raton, and there is a large mass of unworked material, which when elaborated will undoubtedly increase the number of species common to these two formations.

The Arapahoe formation has a flora of 32 species, nearly all of which have been found also in the Denver. The flora certainly lends support to the view that they are not greatly different.

On the south and southeast of the Denver basin is the area occupied by the Dawson arkose, which, as already stated, is believed to be stratigraphically continuous with the Denver and Arapahoe formations; the difference between them being largely lithological, the Denver being andesitic and the Dawson arkosic. The flora of the Dawson numbers between 30 and 40 species, nearly all of which are typical and well known Denver species. There can be no doubt, therefore, that the two are of the same age. The correlation of the Denver and the Raton is also well attested by the flora.

The plant-bearing beds in North Park, Colorado, may next be considered. There is very little topographic relief within this area, with the result that exposures of the strata are few and usually poor. The coal-

bearing and plant-bearing beds appear to rest on marine beds perhaps as old as the Mancos, the Laramie, so far as known, being absent. The flora in these beds, although small, is undoubtedly the same as that in the "Upper Laramie" near Carbon. Dinosaurs have not been found in North Park, though they are abundant in the beds in Carbon County, Wyoming.

The flora of the "Upper Laramie" in Carbon County embraces about 70 species, of which number nearly one-half are common to the Lance of other areas, and there are also large unworked collections that will probably still further augment the number of common species. As already indicated, five or six of these species are known in the underlying "Lower Laramie."

We have now come to the consideration of the flora of the Lance. I have already shown that the Lance formation is inseparable—structurally and lithologically—from the overlying Fort Union, and the flora is likewise so markedly of Fort Union facies that it is often quite impossible to distinguish the one from the other without stratigraphic or other data. As the Tertiary age of the Fort Union is admitted by every one, it is not necessary to dwell on this point. It has a large flora of perhaps 500 species, many of which are still undescribed.

The Lance flora embraces about 100 named and described species, as well as a considerable number not yet described. Of these 100 species, over 75 are typical Fort Union species that have never been found in older beds and most of them only in the Fort Union. I am, of course, well aware that statistics may mean little or much, depending on how they are compiled—that is, the mere presence of a species in a list may have little significance or real value. In the present case, however, many of these Lance species are found at dozens of localities and often in hundreds of individuals. To any one familiar with the Fort Union flora, its preponderating element in the Lance flora is apparent.

The evidence regarding the post-Cretaceous floras has now been presented for the vast area which extends from New Mexico to Alberta. It has been shown that in the south the Raton formation is to be correlated with the marine Eocene of the Gulf region, and step by step the correlation through the Dawson, Denver, and Lance has been traced until it merges inseparably with the Fort Union, which is of acknowledged Eocene age.

DIASTROPHIC EVIDENCE

I had hoped to be able to present certain diastrophic evidence, which I consider of the highest importance, if any serious attempt is to be made in settling the Cretaceous-Tertiary boundary, but it has been deemed

inexpedient to discuss this at the present time. I may only say, therefore, that we are not concerned with the various theories as to why the earth changes its form, but simply that it does do so, which is unquestioned. That these changes or crustal movements are periodic in their action is also evident, and, moreover, it is possible to demonstrate a certain amount of rhythm in these activities. That is to say, while some of these movements have obviously been more or less local in their action, others have been not only continent-wide, but practically and simultaneously world-wide. These grand periods of diastrophic activity, which have been variously called "revolutions," "critical periods," or "grand cycles" in the history of the earth, have long been recognized and accepted by most geologists. According to Ulrich, there have been at least four such major periods of activity on the North American continent, the latest important one being the one here involved, namely, at the close of Cretaceous time.

The Cretaceous was a period of maximum sea extension throughout the world, and its close was marked by maximum sea exclusion. According to Schuchert's paleographic maps of North America, the Cretaceous Sea was spread over a wider continental area than had previously been occupied by marine waters since perhaps Silurian or Devonian time. The Eocene witnessed the sea withdrawal in Europe as well as in North America.

THE EUROPEAN TIME SCALE

This is perhaps an opportune point at which to consider the so-called European standard and to compare it with the American conditions and requirements. In this connection I must express my indebtedness to Mr. W. T. Lee, who has spent much time in consulting the literature.

It is recognized that the subdivision of stratified rocks into systems is imperfect. Probably no system is completely represented in any one place. It is recognized that the type locality of a system may not contain its fullest expression as to range and age. Hence a type standard—such, for example, as the European standard—is at best only temporary, since it was based on incomplete information and must eventually give place to a standard of world-wide application. It is, therefore, obviously unwise to set up a European standard for measuring American systems, as if that standard were final. I say *a* European standard rather than *the* European standard, for there are disagreements among European geologists as to the line of separation between Cretaceous and Tertiary just as there are in America.

In order to answer the question "How does the European standard aid

in drawing the line of separation between the Cretaceous and Tertiary in America?" it is necessary to go back and determine at several critical points what constitutes this standard.

The Cretaceous and Tertiary systems were worked out in the Anglo-Parisian basin. The type area of the Cretaceous—or Chalk, as it was called until 1822, when d'Halloy introduced the term Cretaceous for it—is in the London basin, and the Tertiary was first worked out near Paris. Geikie says, concerning them, that both in France and in England "the lithologic sequence, being the more obvious, was first established before it was confirmed and extended by a recognition of the value of the evidence of organic remains." This statement, that the systems were established on a physical basis, is abundantly verified by the early writings. As the systems were studied in other regions, conflict of opinions developed as to the position of the Danien and Montien beds, which seem to contain a mixture of Cretaceous and Tertiary forms. Some of the European geologists place these formations in the Cretaceous, others in the Tertiary, while Dollo, Haug, and others assign the Danien to the Cretaceous and the Montien to the Tertiary. It is significant that, although several fossils of Cretaceous type occur with those of Tertiary type in the Montien, Haug reverts to the original criteria for determining the separation between the two systems, and places the Montien in the Tertiary because it lies unconformably on the older rocks.

In his summary of the Montien, Haug states that it contains, together with Tertiary forms, several survivors of the Cretaceous faunas, among which are crocodiles, magalosaurus, and other dinosaurs.

Two things mentioned above are especially significant: (1) The Cretaceous and Tertiary systems were originally established on a physical basis, and the exact line of separation between them was determined by the structure; (2) after more than a century, during which the several lines of evidence have been tested, the last authoritative word on the European standard is to the effect that the structure is the determining factor in separating them, and that even dinosaurs, that have been appealed to so often as proof of Cretaceous age, did not end with the Cretaceous.

Probably all American geologists will agree as to the desirability of conforming the American geologic time scale as closely as possible to the European standard, and probably all who have thought seriously on the subject will also agree that it is impracticable, perhaps impossible, to do so in all cases. "I do not hesitate to express the opinion," said the late Dr. C. A. White,⁵ "that it [the European standard] is not of infallible

⁵ Proc. Amer. Assoc. Adv. Sci., vol. 38, 1889, p. 225.

application to other parts of the world, except perhaps as to its larger divisions, and that even in this respect it will need modification."

VERTEBRATE EVIDENCE

I shall have very little to say regarding the vertebrate evidence. If the presence of dinosaurs is to be taken as *prima facie* indication of Cretaceous age, then this discussion might as well end at once, for it is beyond question that dinosaurs are present in beds above the unconformity which, in my opinion, separates Cretaceous from Tertiary.

Vertebrate paleontologists have claimed that the dinosaur fauna of the Lance, Denver, etcetera, does not give any indication of this time break, thereby implying that there is a dinosaur fauna immediately below the unconformity which can be directly compared with the Ceratops fauna. But is this true? So far as known to me, from field observations and a study of the literature, dinosaurs have not been found in the beds which immediately underly the unconformity—that is, in Laramie, Fox Hills, uppermost Pierre, etcetera—except possibly in Alberta and below the Puerco formation, where the relations are in doubt.

The nearest dinosaur fauna with which that of the "Ceratops beds" can be compared is in the Belly River, which is stratigraphically some 2,000 feet below the unconformity, and when we make this comparison we find, I am told by Mr. Gilmore, that not a single species, and perhaps only a single genus, is common to Belly River and "Ceratops beds." The Ceratops fauna, therefore, proves clearly that there has been a very distinct change in passing over the line of the unconformity.

A word may be said regarding the Edmonton of Canada, which has been supposed to be the same as the Lance formation of the United States. According to Barnum Brown, the dinosaur fauna of the lower portion of this formation—the so-called lower Edmonton—is distinctly more primitive than that of the Lance, being in fact much more closely related to that of the Belly River. In one of his later papers, dealing with this field, Mr. Brown has announced his intention of establishing a new formation for this lower Edmonton; but until the full data, stratigraphic as well as paleontologic, have been published it is perhaps useless to speculate further concerning the fauna. I may say, however, that Mr. Brown has kindly permitted me to study the fossil plants of the Edmonton section, and I have found them, with the following exception, to be uniformly of Fort Union or Lance types. The collection from 16 miles below Tolman, in beds stated on the labels accompanying the specimens to be lower Edmonton, is distinct from anything before submitted to me.

This lot contains a Ginkgo nearest to and probably identical with *Ginkgo laramiense* Ward, from Point of Rocks, Wyoming, a cycad—*Pterophyllum*—of a type not found above the Cretaceous, and two species of dicotyledons; *Viburnum*, an unpublished species from Point of Rocks, and *Platanus wardii* ? Kn., from the lower Montana of the Missouri River below Coal Banks, Montana.

In my opinion, this collection has a distinct Cretaceous aspect, though it is obviously too small to predicate positively its age. This may explain why the fauna exhibits such an evident affinity with that of the Belly River. I am forced to the conclusion that two very distinct horizons may have been confused under the name of Edmonton. It is just possible that this may be the long lost Laramie fauna.

This issue can not be avoided, as Doctor Matthew and others have proposed doing, by extending the definition of Laramie from a *formation* to a *group*, for then we shall not only contravene the original definition, but we shall have the anomalous condition of the "*Laramie group*" being divided by a major unconformity and falling within two systems. The original pronouncement of King, and as emphasized by Cross, Peale, and others, fixes the Laramie as "the uppermost member of the conformable Cretaceous series above the Fox Hills." Being *above* an unconformity, the "Ceratops beds" are not a part of the "conformable Cretaceous series," and hence can not be Laramie. This condition was correctly appreciated by Barnum Brown, who, in his paper on the "Hell Creek beds," says: "Strictly following King's definition of Laramie, neither of these deposits ["Hell Creek beds," "Ceratops beds," etcetera] can be considered as such, for neither one represents a continuous sedimentation from the marine Fox Hills. They should therefore be grouped with the Livingston, Denver, and Arapahoe beds and may be considered post-Laramie."

It was thought at one time that the ceratopian dinosaurs might be found in the same beds with the Puerco mammals, but, according to Doctor Sinclair, apparently this is not so. The Puerco formation rests unconformably on dinosaur-bearing beds, beneath which is the "Laramie" of the region. I have shown elsewhere, however, that these latter beds are undoubtedly much older than Laramie. The "Ceratops beds," immediately beneath those containing the Puerco fauna, have been practically traced into the Animas formation, which Cross holds is of Denver age. The Animas formation is now known to extend eastward to the eastern border of the San Juan basin, near Dulce, New Mexico, where it is conglomeratic at the base and consists of an andesitic matrix, in which are pebbles of many kinds of older rocks; above this conglomerate are Eocene leaves.

INVERTEBRATE EVIDENCE ⁶

In ninety-nine one-hundredths of the area over which the dinosaur-bearing beds are distributed there are either no invertebrates at all or they are fresh-water forms, which are generally recognized as of little value in fixing age. Marine invertebrates have come into this discussion from limited areas in North and South Dakota, where it is claimed they have been found in or above the Lance.

In North Dakota from the Cannonball River northeast to Heart River, a distance of perhaps 75 miles, is a long, narrow, somewhat irregular area of sandy shales and sandstones from 200 to 300 feet in thickness which contains a considerable marine fauna. This has been called the Cannonball marine member of the Lance formation. Its proposers, Messrs. Winchester, Hares, and Lloyd, of the United States Geological Survey, defined its top as the highest point at which marine invertebrates have been found, and its base as the highest point at which dinosaurs occur. It was regarded by its proposers as a lens in the Lance formation, and is considered in whole or in part as the marine equivalent of a non-marine, coal-bearing horizon to which the name Ludlow lignitic member of the Lance has been given.

Three possible explanations have been advanced by different geologists to account for the presence of this Cannonball member: (1) That it is a lens in the Lance, in which case it must have resulted from a temporary invasion of the sea after the inauguration of Eocene time; (2) that it is an erosion remnant of Fox Hills, surrounded by and projecting through the Lance, or (3) that Fox Hills time continued through Lance to Cannonball time.

The first of the alternative explanations—that the Cannonball is above or a lens in the Lance—was the one adopted by the original namers of the member, is still entertained by them, and has been accepted by the United States Geological Survey.⁷ This means that the Cannonball is separated from the Fox Hills by 400 feet or more of Lance beds—that is to say, that marine conditions similar to those of the Fox Hills were restored for the short interval of Cannonball time after the deposition of the fresh-water Lance beds. It has in its favor the following points: (1) Its position is above the Lance; (2) it is not known to be structurally connected with the Fox Hills; (3) its fauna, though differing somewhat, is apparently most closely related to that of the Fox Hills; (4) it

⁶ See Knowlton, *Proc. Wash. Acad. Sci.*, vol. 11, 1909, pp. 226-228.

⁷ Lloyd: The Cannonball River Lignite field, North Dakota. *Bull.* 541G, U. S. Geol. Survey, 1914, pp. 1-51.

may be a recurrent fauna surviving from the Fox Hills fauna, which is itself partially recurrent from the Claggett (lower Montana). But this explanation requires a connection with the sea, presumably after the inauguration of Eocene time.

CONCLUSIONS

The thesis of this paper, as stated at the beginning, is that the line between Cretaceous and Tertiary in the Rocky Mountain region is to be drawn at the base of the dinosaur-bearing and equivalent beds—that is, at the base of the Lance, “Ceratops beds,” “Hell Creek beds,” “Somber beds,” Arapahoe, Dawson, Raton, and “Laramie” of many writers. Evidence, believed to be competent, has been presented in support of this view from the side of stratigraphy, diastrophism, and paleobotany, and what is thought to be the weakness and insufficiency of the vertebrate and invertebrate evidence has been pointed out. The vertebrate paleontologist would place the Cretaceous-Tertiary line at the highest horizon at which dinosaurs are found, notwithstanding the fact that this is a variable boundary unattended by structural or diastrophic action. The invertebrate paleontologist would place this line at the highest point where marine invertebrates of Cannonball types occur. The paleobotanist would place the line at the lowest horizon at which Tertiary plants have been found which corresponds with the structure. The paleontologists are not in accord. It is unlikely that they will ever be in complete agreement. What, then, is to be the court of final appeal? There is but one answer: Structure resulting from diastrophism. The evidence from these sources supports the thesis. Why, then, shall we not be logical and rational, and agree to place the line where nature plainly indicated it rather than at some shifting, vague, and indefinite point simply to maintain a tradition?

BOUNDARY BETWEEN CRETACEOUS AND TERTIARY IN NORTH AMERICA AS INDICATED BY STRATIGRAPHY AND INVERTEBRATE FAUNAS¹

BY TIMOTHY W. STANTON

(Presented before the Paleontological Society December 31, 1913)

CONTENTS

	Page
Typical Cretaceous and Eocene of western Europe.....	341
Contact between marine Cretaceous and marine Eocene in North America.....	342
Variations in Upper Cretaceous sedimentation of the Interior Province...	343
General discussion.....	343
Evidence of land areas in the Rocky Mountain region.....	344
Evolution of unconformities.....	347
The Lance formation.....	348
Distribution and general character.....	348
Development in North and South Dakota.....	349
Review of investigations.....	349
Lower member and its relations with the Fox Hills.....	350
Marine member and its Cretaceous fauna.....	351
Conclusion.....	353

TYPICAL CRETACEOUS AND EOCENE OF WESTERN EUROPE

It should be remembered at the outset that the Cretaceous system was first described in England, and that the Anglo-Parisian basin can perhaps with justice be considered the typical area of both Cretaceous and Eocene. Among English geologists there has been some difference of opinion concerning the real character of the boundary between Cretaceous and Eocene, but the statement by Geikie in his text-book may be accepted as conservative. He says: "In England the interval between the Cretaceous and the next geological period represented there by sedimentary formations is marked by the abrupt line which separates the chalk from all later accumulations, and by the evidence that the chalk seems to have been in some places extensively denuded before even the oldest of what are called the Tertiary formations were deposited upon the

¹ Manuscript received by the Secretary of the Geological Society June 14, 1914.

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surface. There is evidently here a considerable gap in the geological record." Remembering that there is also a very remarkable faunal break here, it is evident from this description that the boundary between Cretaceous and Tertiary as originally established complied with all the demands of the most advanced modern school of stratigraphy in which diastrophism theoretically holds the highest place. The old-time paleontologists were also equally well pleased with the boundary because the marine invertebrate faunas on either side of it are in very sharp contrast. Not only is there an abrupt change in the species, but many genera, families, and even orders which flourished in the Cretaceous do not pass beyond its upper limits, while many new types are introduced in the succeeding Eocene.

Where such conditions exist, as they do in many parts of Europe, there is no difficulty in fixing the limits between Cretaceous and Tertiary; but in Denmark, in Belgium, in the middle of the Paris basin, and in some other parts of Europe there are deposits, in part marine and in part continental, which seem to belong between the highest Cretaceous and the lowest Eocene represented in England. These intermediate deposits have been called Danian, Montian, and other more local names, and have been assigned by some geologists to the Cretaceous, by others to the Tertiary, and by still others part to the Cretaceous and part to the Tertiary. The limits that have been given to Danian and Montian and the various senses in which these names have been used by different geologists show almost as great variety in usage as our own much abused term Laramie has received. It is interesting to note that the latest European dinosaurs come from formations concerning whose classification perfect agreement has not yet been reached.

All will agree, I think, that when two contiguous systems as originally defined are separated by an unconformity or there is other evidence of a break in sedimentation, it is probable that intermediate deposits will be found in some part of the world, and that when found, if they are subordinate in character, they should be assigned in each case to the system to which they are most closely related. The practical difficulty lies in demonstrating the close relationship, and that difficulty is not removed by applying new criteria and new principles of classification or by redefining a system to make it fit local conditions in a restricted distant area without consideration of the type section.

CONTACT BETWEEN MARINE CRETACEOUS AND MARINE EOCENE IN NORTH AMERICA

In America, as in England, wherever marine Cretaceous is directly overlain by marine Eocene there is no difficulty in recognizing the bound-

ary between them, and there is no controversy concerning the boundary. Dr. L. W. Stephenson has emphasized this fact for the Atlantic and Gulf coastal plain of the United States in a paper recently presented to the Geological Society of Washington, but not yet published. He showed that at many places where the actual contact between Cretaceous and Eocene is visible there is evidence of an interval of erosion, and he stated that the faunas are so distinct that they suggest a very long unrecorded interval. Such a suggestion of a very long interval should be received with caution, however, for the reason that very few if any of the Eocene species can be supposed to be directly descended from Cretaceous species of the same area. They are immigrants from some other region, and we have no record of the time that was required for their development.

The only other area in North America where marine Eocene is known to follow marine Cretaceous is on the Pacific border west of the Sierra Nevada and Cascade ranges. For many years it was believed that there was a gradual transition from the Cretaceous to the Tertiary in California, and that this transition was marked by a mixed fauna, in which many persistent Cretaceous species were associated with Eocene types. It is now known that this belief was erroneous, and that it was caused by imperfect knowledge of both the stratigraphy and the paleontology of the region. The detailed stratigraphic and faunal studies of Merriam,² Weaver,³ Dickerson,⁴ and others, with some of my own earlier work,⁵ have shown that the boundary between Cretaceous and Eocene is as distinct on the Pacific coast as it is on the Atlantic side of the continent. In both these areas the close of the Cretaceous is marked by uplift and consequent withdrawal of the sea and the Eocene begins with the return of the sea, though it is extremely doubtful whether the limits of the interval between the retreat and return of the sea are the same in both areas.

VARIATIONS IN UPPER CRETACEOUS SEDIMENTATION OF THE INTERIOR PROVINCE

GENERAL DISCUSSION

In the Interior Province, including the Great Plains and Rocky Mountain regions, conditions were different. The Upper Cretaceous Sea dur-

² J. C. Merriam: The geologic relations of the Martinez group of California at the typical locality. *Journal of Geology*, vol. 5, 1897, pp. 767-775.

³ C. E. Weaver: Contribution to the paleontology of the Martinez group. *Cal. Univ. Publ. Bull. Dept. Geol.*, vol. 4, 1905, pp. 101-123.

⁴ Roy E. Dickerson: The stratigraphic and faunal relations of the Martinez formation to the Chico and Tejon north of Mount Diablo. *Cal. Univ. Publ. Bull. Dept. Geol.*, vol. 6, 1911, pp. 171-177.

⁵ T. W. Stanton: The faunal relations of the Eocene and Upper Cretaceous on the Pacific coast. *Seventeenth Ann. Rept. U. S. Geol. Survey*, pt. 1, 1896, pp. 1011-1060.

ing the Colorado epoch covered a large part if not the whole of the province, and by the end of the Cretaceous it had entirely retreated from the area; but the Eocene Sea did not return into this province at all. Instead of marine deposits great continental deposits were formed, beginning in the Cretaceous and continuing with many interruptions and with increasing restriction of areas throughout Tertiary time. In the early days of geological exploration of the Rocky Mountains and Great Plains many geologists believed that all these continental deposits are Tertiary; but with greater knowledge of the history of the region that idea was long ago abandoned, and many of the continental formations have been recognized as of Cretaceous age, especially those that were subsequently covered by marine Cretaceous sediments.

EVIDENCE OF LAND AREAS IN THE ROCKY MOUNTAIN REGION

A brief consideration of some facts in the history of the province during later Cretaceous time will aid in the correct interpretation of events nearer the close of the period. On another occasion⁶ I have pointed out some of the variations in the sedimentary record which clearly show that conditions were not uniform throughout the region. The idea has sometimes been expressed that this was a period of quiet and universal submergence for the province with no land-masses within it until the end of the period when the whole area was lifted above sealevel by a single movement. There are many facts opposed to this view—so many that they form convincing evidence that at several times during the period there were differential movements which brought previously submerged local areas above sealevel. The greatest extension of the sea and presumably the deepest submergence seems to have been near or after the middle of the Colorado epoch; but even at that time it is probable that there were large islands. The local variations in thickness and character of the sediments bespeak the nearness of land at some localities.

No argument is needed in support of the statement that a coarse conglomerate among marine sediments generally means the proximity of land or that coal beds were formed above sealevel, especially when they are accompanied by strata full of the well preserved foliage of land plants or with an abundant fresh-water fauna. By these and other criteria it can be shown that in many parts of the Rocky Mountain region there were uplifts which made land of parts of the Cretaceous area in both the Colorado and Montana epochs, and that these movements were not suffi-

⁶ Timothy W. Stanton: Some variations in Upper Cretaceous stratigraphy. *Jour. Washington Acad. Sci.*, vol. 3, 1913, pp. 55-70.

ciently general to drain the sea from the whole region. A few examples will suffice.

In the Datil Mountain area of western New Mexico coal-bearing strata, with a land flora, were deposited early in the Colorado epoch. These were again covered by the sea, but near the close of the Colorado the area again emerged and received a thick series of continental deposits, with many thin coals and numerous land plants. So far as the record shows the sea never again invaded this particular area. Farther north in New Mexico and in southwestern Colorado marine sedimentation was continuous throughout the Colorado epoch, and it was not until later in the Montana epoch, at the time represented by the Mesaverde formation, that the land emerged sufficiently to support forest growth and permit the formation of coal beds. It is true that the Mesaverde formation includes some marine strata, but it consists in large part of non-marine beds deposited above sealevel. These continental deposits of the Mesaverde formation cover large areas in western Colorado, in eastern Utah, and in southern Wyoming from the Laramie Plains westward.

East of the mountains in Colorado and a part of Wyoming there was no break in marine sedimentation⁷ in either the Colorado or the Montana epoch. There is, however, some evidence of differential movement and of locally derived sediments in both epochs. In the Colorado group a sandstone is developed as the uppermost member of the Benton immediately beneath the limestone of the Niobrara. This sandstone at some localities in Huerfano Park, southern Colorado, is 40 feet thick and contains an abundant littoral fauna, which, like the sands in which it is embedded, indicates a near-shore deposit. It is 20 feet thick in the Arkansas Valley above Pueblo, and northward decreases to 3 or 4 feet in northern Colorado.

North of Denver, in Colorado, the middle and upper parts of the Pierre shale contain a large proportion of marine sandstones (of which the Hygiene sandstone member is an example). Lithologically these sandstones resemble the sandstones of the Mesaverde formation in northwestern Colorado and in the Laramie Plains and other parts of southern Wyoming, and as they occupy approximately the stratigraphic position of the Mesaverde it is probable that their materials were derived from the erosion of the same land-masses. Other areas of land in the Colorado epoch are indicated by coal-bearing formations in the Harmony, Colob, and Kanab coal-fields of southern Utah, in northern Utah, at Coalville, and in western Wyoming, in the important coal-bearing members of the

⁷ Possibly the local structural breaks described by Eldridge in the Denver Basin are an exception. See Monograph U. S. Geol. Survey, vol. 27, pp. 91-111.

Frontier formation. At Coalville there is also the evidence of a very coarse conglomerate 60 feet thick at or near the top of the Colorado group. There are lenses of coarse conglomerate near the middle of the Colorado at Cody, in Bighorn basin, Wyoming, and a still greater development of conglomerate at about the same horizon at Livingston, Montana. These conglomerates are unquestionably near-shore deposits, which indicate land of considerable elevation.

During the Montana epoch there is abundant evidence of oscillating movements and resulting more or less temporary land conditions from northern Wyoming northward through Montana and in the Canadian territories. This is seen in the coal beds and land plants of the Eagle sandstone and the coals and land and fresh-water faunas of the Judith River formation, in each case found in formations interstratified with purely marine deposits. In the Blackfoot Indian reservation and farther north beyond the international boundary the ratio of continental to marine deposits was greatly increased, and during the epoch there was only one decided incursion of the sea, represented by the Bearpaw shale, which passes by gradual transition through overlying littoral and brackish-water deposits into continental deposits. In the Bighorn basin the final change from marine to continental deposition came earlier, near the beginning of the Montana.

In the country surrounding the Crazy Mountains and near Livingston, Montana, there is evidence of another kind that the late Cretaceous was not a time of quiet, uniform, marine submergence. On the contrary, there was great volcanic activity, beginning early in the Montana epoch, while the Eagle sandstone was being deposited and continuing, probably with many interruptions, until well into the Eocene, or at least furnishing material for sediments until that date. The debris from these eruptions was deposited in part above sealevel and in part beneath it, in some places fingering out between more nearly normal marine sediments. These andesitic tuffaceous deposits constitute the Livingston formation, which was described by Weed 20 years ago as resting unconformably on the "Laramie," and which has frequently been cited as similar to the Denver formation in character, relations, and age. The more detailed stratigraphic and areal work of Stone⁸ and Calvert has shown that the unconformity described by Weed as at the base of the Livingston has no existence in fact, and that while the upper part of the formation may be as late or even later than the Denver a large part of it was formed during

⁸ R. W. Stone and W. R. Calvert: Stratigraphic relations of the Livingston formation of Montana. *Economic Geology*, vol. 5, 1910, pp. 551-557, 652-669, 741-764.

Montana time. This is one example of the failure of the "great post-Laramie unconformity" to hold its place.

EVOLUTION OF UNCONFORMITIES

Enough evidence and examples have been given to emphasize the fact that the Upper Cretaceous in the Interior Province was an epoch of repeated differential movements which brought now one area, now another, above sealevel. With such a record the question is, When did the Cretaceous period end? The retreat of the sea from any particular local area can not be taken as a criterion because, as we have seen, the time of the final retreat varied considerably from place to place. Even in the Denver basin this final retreat occurred before the close of the Cretaceous. All are agreed in referring the Laramie of the Denver basin to the Cretaceous because it rests conformably on the marine Cretaceous Fox Hills and represents a transition from marine to non-marine conditions. Its upper part was formed above sealevel. Now as soon as an area is elevated above the sea and, even before that, as soon as it is brought within reach of strong tidal currents it necessarily becomes more or less subject to erosion. For this reason an erosional unconformity in estuarine or continental deposits may have very little time significance and its importance must be tested by paleontologic and other criteria. Likewise a conglomerate in continental deposits has no such essential importance as a basal conglomerate of a marine formation. It may mean only a slight change in the grade of a stream, or even nothing more than a change in climate which has made erosion and transportation more active.

Full consideration should be given to the physical evidence of the post-Laramie unconformity in the Denver basin and to the sudden change in the lithologic character of the formations which follow it; but in my opinion the length of the erosion interval between the Laramie and the Arapahoe, which immediately succeeds it, has been very greatly exaggerated on account of a wrong conception of the history and physiographic condition of neighboring areas during later Cretaceous time. It has been supposed that the post-Laramie-pre-Arapahoe interval is measured by the erosion of at least 14,000 feet of sediments because the conglomerates of the Arapahoe contain pebbles derived from formations stratigraphically that far below the top of the Laramie. But this supposition is based on the assumption, which I believe to be unwarranted, that there were no upward movements and no lands subjected to erosion in adjacent areas from the beginning of marine Cretaceous sedimentation in the region to the close of the Laramie.

Granting that the post-Laramie diastrophic movement was important,

and that the erosion interval may have been long in the Denver basin, there are still other questions to be considered before deciding that the break marks the boundary between Cretaceous and Tertiary. How great an area was affected by the movement? Can the break be identified with the one which separates marine Cretaceous from marine Tertiary in other areas? What is the testimony of paleontology in all its branches concerning the relationships of the faunas and floras in the formations immediately above the unconformity?

The answers to these questions are not all harmonious, but some progress has been made toward ascertaining the facts, and this conference ought to mark another step in advance. The presence of andesitic material in sediments can not now be accepted as evidence that "the great unconformity" is beneath it, nor can the occurrence of ceratopsian dinosaurs be taken as proof of general diastrophism just before they came on the scene. The unconformity beneath the Livingston has disappeared. The unconformity described by Veatch in southern Wyoming between "Lower Laramie" and "Upper Laramie" must await more detailed areal and stratigraphic studies before it can be properly evaluated. It will suffice for the present to state that in the only area where his "Upper Laramie" which has yielded Triceratops or dinosaurs of any kind, the "Lower Laramie" also contains ceratopsian remains, and that the two geologists (Beekly and Bowen) who have recently examined the area in detail have failed to find there any conclusive evidence of unconformity between the Triceratops-bearing beds and the "Lower Laramie." The post-Vermejo unconformity of northern New Mexico has been correlated by Lee and Knowlton with the post-Laramie unconformity of the Denver basin on the evidence of fossil plants in the overlying Raton formation, and this correlation may be correct. No other classes of fossils have been found here to serve as a check on the plants.

THE LANCE FORMATION

DISTRIBUTION AND GENERAL CHARACTER

It will be remembered that in eastern Wyoming, South Dakota, North Dakota, and some other areas north of the Denver basin it has not been possible to agree on the proper use of the term Laramie, and therefore the non-committal name Lance formation has been adopted for the non-marine dinosaur-bearing formation, formerly called "Ceratops beds" and various other names, overlying the Fox Hills sandstone where that formation as such is present. The Lance formation has a vertebrate fauna which is closely related to the fauna of the Denver formation and less

closely to the Judith River fauna; a brackish-water invertebrate fauna developed locally in its lower part, which is in part identical with the Laramie fauna and is evidently derived from older Cretaceous faunas; a fresh-water invertebrate fauna which is in part restricted to the Lance, in part identical with the Laramie, with a few forms passing up into the Fort Union, but altogether much more closely allied to Cretaceous than to Tertiary faunas, and a flora which is closely related to the Fort Union flora and regarded by Knowlton as somewhat younger than the Denver flora.

DEVELOPMENT IN NORTH AND SOUTH DAKOTA

Review of investigations.—In 1910 I published evidence⁹ tending to prove that in eastern Wyoming and the Dakotas there is gradual transition with practically continuous sedimentation from the Fox Hills sandstone into the Lance formation, and that the local erosion, of which there is evidence, in some places could not represent any important time interval. Stratigraphic details and faunal lists from localities in the Standing Rock and Cheyenne River Indian reservations made it clear that the erosion and other phenomena, believed to indicate a break, occurred while the marine Cretaceous Sea was still present. In the same paper attention was called to an oyster-bed in the Lance formation near Yule, on the Little Missouri, North Dakota, in strata approximately 500 feet above the base of the formation and a less distance above beds in the same neighborhood containing Triceratops and other dinosaurs. This oyster-bed was cited as evidence that the Cretaceous Sea was still near enough to send its tidal brackish waters to the Yule locality. It is now known that that sea lay to the eastward in southern North Dakota and northern South Dakota, and that its marine sediments, with a thickness of 200 or 300 feet, forming a marine member of the Lance formation, cover the 400 feet of continental deposits belonging to the same formation which overlie the Fox Hills sandstone in the Indian reservations just mentioned. It is not possible and it would not be appropriate for me to give the full evidence for this statement at this time; but the facts of stratigraphy and areal distribution on which it is based are well known, and will be published in detail in a series of reports in press and in preparation by members of the Western Fuel section of the United States Geological Survey. These reports describe a connected area extending from the Missouri River across the Standing Rock and Cheyenne River reservations to the western boundary of North and South Dakota. The Indian reservations are de-

⁹ Fox Hills sandstone and Lance formation ("Ceratops Beds") in South Dakota and eastern Wyoming. *Amer. Jour. Sci.*, vol. 30, 1910, pp. 172-188.

scribed¹⁰ by W. R. Calvert, A. L. Beekly, M. A. Pishel, and V. H. Barnett, and other separate parts of the area are treated by E. Russell Lloyd, D. E. Winchester, E. M. Parks, and C. J. Hares. The marine member of the Lance formation and its stratigraphic relations will be especially described and discussed in the current volume of the *Journal of Geology* in a paper by Messrs. Lloyd and Hares, who first discovered it and have collected most of the data concerning it. This marine member has such an important bearing on the topic of the present discussion—the boundary between Cretaceous and Eocene—that it must be briefly considered, and in order to explain that bearing it is necessary to review some facts in the history of investigation and discussion of the geology of the area during the past four years.

Lower member and its relations with the Fox Hills.—The mapping of the Indian reservations by Calvert and his assistants and of the Bismarck quadrangle by Leonard¹¹ developed the fact that the Fox Hills sandstone, with its marine Cretaceous fauna, is exposed for many miles along the Missouri River, extending as far north as old Fort Rice, about 20 miles below Mandan, and that it is also exposed for considerable distances up the Cannonball, Grand, and Moreau rivers. Throughout this area the Fox Hills sandstone is immediately overlain by non-marine deposits, which in many localities weather into bad-lands forms and have been referred to the Lance formation on the evidence of the vertebrate fauna. Dinosaur bones are widely distributed through the beds, and at a few places, as, for example, in section 12, township 20 south, range 22 east, near Grand River, nearly south of McIntosh, South Dakota, the bones are abundant and well enough preserved to be identified as Triceratops, Trachodon, etcetera, clearly belonging to the Lance fauna. At this place the dinosaurs are less than 50 feet above the base of the formation. A considerable flora has been listed by Knowlton¹² from 10 localities in these same deposits, ranging in stratigraphic position from 4 feet to 300 feet above the base of the formation. Knowlton says of it: "The plant collections obtained from the Lance formation by Mr. Calvert and the members of the several parties under his charge show conclusively that the relation of this flora is unmistakably with the Fort Union. In fact, with the information at hand regarding distribution, it is practically impossible without stratigraphic data to distinguish

¹⁰ Geology of the Standing Rock and Cheyenne River Indian Reservations, North and South Dakota. Bull. 575, U. S. Geol. Survey.

¹¹ A. G. Leonard: Bismarck folio (No. 181), Geol. Atlas U. S. U. S. Geol. Survey, 1912.

¹² Further data on the stratigraphic position of the Lance formation ("Ceratops Beds"). *Journal of Geology*, vol. 19, 1911, pp. 358-376.

between the flora of the Lance formation and that of the acknowledged Fort Union." There was agreement, therefore, that these non-marine beds immediately above the Fox Hills are Lance, or at least not older than Lance.

The contact between the Fox Hills and the Lance in this area shows irregularities at some localities which have been interpreted as proof of an unconformity and erosion interval. In the paper just cited Knowlton publishes a statement by Calvert advocating this interpretation, and he adds his own opinion concerning the magnitude of the unconformity in these words: "Whether the Laramie and various post-Laramie beds were deposited and later removed throughout the Dakotas, Montana, and Wyoming is not at present known, but certain it is that the unconformity at the base of the Lance formation represents the time interval during which in other areas they were laid down and subsequently removed in whole or in part." Presumably in this case "various post-Laramie beds" means Arapahoe and Denver and the associated unconformities. My own conclusion that there was practically no hiatus here at the base of the Lance and the evidence in support of that conclusion have already been cited.

Marine member and its Cretaceous fauna.—In the summer of 1912 Mr. E. Russell Lloyd began the examination of the area immediately north of the Standing Rock Indian reservation in the valley of Cannonball River and its tributaries. He there found marine invertebrate fossils at a number of localities believed to be in the Lance formation several hundred feet above its base, and these fossils were identified as belonging to the Fox Hills fauna. Mr. C. J. Hares also found a few marine fossils of the same character at apparently about the same horizon much farther west near the headwaters of Grand River.

Mr. Lloyd's work during 1913 has multiplied the localities and greatly extended the area in which this marine fauna is found, so that the known localities are distributed in a belt extending from old Fort Lincoln, on the Missouri, near Mandan, North Dakota, to Haley, North Dakota, on the north fork of Grand River, a distance of more than 100 miles. His work has also fixed the position of the marine member in the upper part of the Lance formation, as locally developed, and above the 400 feet of non-marine Lance which contain Triceratops and other reptilian fossils, with a flora that is said by Knowlton to be indistinguishable from the Fort Union flora, and hence believed by him to be Eocene.

In my opinion, the invertebrates from the marine member of the Lance belong to a Cretaceous fauna. This is indicated both by their close relationship with the Fox Hills fauna and by the known paleogeographic facts of the late Cretaceous and the Eocene. The fauna contains a num-

ber of species identical with Fox Hills forms, others that are closely related, a few that were ascribed to the Fox Hills, but apparently were actually collected by the early explorers from beds now assigned the marine member of the Lance, and a considerable number of new species, which so far as known do not occur outside of the marine member.

The list of forms recognized is as follows:

- | | |
|--|---|
| <i>Nodosaria</i> sp. | † <i>Teredo selliformis</i> M. and H. |
| <i>Caryophyllia</i> ? sp. | <i>Corbula</i> sp. |
| <i>Anomia</i> sp. | <i>Entalis</i> sp. |
| <i>Perna</i> sp. | <i>Scala</i> ? sp. |
| <i>Crenella</i> sp. | <i>Turritella</i> ? sp. |
| * <i>Cucullæa shumardi</i> M. and H. | ‡* <i>Lunatia concinna</i> (H. and M.) |
| † <i>Glycimeris subimbricata</i> (M. and H.) | <i>Cerithium</i> ? sp. |
| * <i>Leda</i> (<i>Yoldia</i>) <i>scitula</i> M. and H. | ‡* <i>Anchura americana</i> (E. and S.) |
| * <i>Leda equilateralis</i> M. and H.? | <i>Anchura americana</i> (E. and S.), |
| * <i>Nucula planimarginata</i> M. and H. | robust variety. |
| ‡ <i>Crassatellites evansi</i> (H. and M.) | <i>Helicaulax</i> ? sp. |
| <i>Solemya</i> ? sp. | †* <i>Cantharus</i> (<i>Cantharulus</i>) <i>vaughani</i> |
| ‡* <i>Lucina occidentalis</i> (Morton) | M. and H. |
| <i>Corbicula cytheriformis</i> M. and H. | * <i>Pyrifusus</i> (<i>Neptunella</i>) <i>newberryi</i> |
| † <i>Cyprina ovata</i> M. and H. | M. and H.? |
| * <i>Cyprina ovata</i> var. <i>compressa</i> M. | * <i>Fasciolaria buccinoides</i> M. and H. |
| and H.? | * <i>Fasciolaria</i> (<i>Piestochilus</i>) <i>culbertsoni</i> M. and H. |
| <i>Veniella</i> ? sp. | * <i>Turris contortus</i> M. and H. |
| <i>Callista</i> sp. a. | <i>Turris</i> sp., related to <i>T. contortus</i> |
| <i>Callista</i> sp. b. | M. and H. |
| <i>Tellina</i> ? sp. | * <i>Turris minor</i> (E. and S.)? |
| <i>Thracia</i> sp., related to <i>T. subgracilis</i> Whitfield | <i>Cinulia</i> sp. |
| † <i>Teredo globosa</i> M. and H. | * <i>Cylichna scitula</i> M. and H.? |

In this list of about 40 forms there are 21 named species and varieties, of which 15 (marked *) occur in the Fox Hills, 4 (marked ‡) occur in the Pierre, and 5 (marked †) were originally described from rocks now known to belong to the marine member of the Lance. One species, *Corbicula cytheriformis*, was described from the Judith River, and is known in the Mesaverde and the Lance of other areas. The fossil seaweed, *Haly-menites major*, which is common in the Fox Hills and other sandy formations of the marine Cretaceous, is also associated with the above listed fauna.

The fauna lacks a number of common Fox Hills species and contains a considerable proportion of new forms, so that it may be called a modified Fox Hills fauna. It gives evidence that the Cretaceous Sea had not yet finally retreated from the province, and it may reasonably be supposed that in some area not far away, probably on the east or southeast,

the sea was present while the lower non-marine member of the Lance was being laid down, so that there were continuous marine conditions from Fox Hills time on until the whole of the marine member was deposited. The fossils do not include any that especially suggest an Eocene fauna, and the geographic location makes it extremely improbable that a marine Eocene fauna could have reached the area, which when located on Professor Schuchert's¹³ paleogeographic map of the Eocene is seen to be almost exactly at the farthest point from known marine Eocene that can be found in the United States, the nearest Eocene localities being the Mississippi Valley near the mouth of the Ohio on the one side, and Oregon west of the Cascade Mountains on the other. If there was general uplift and long continued erosion throughout the province preceding the Lance, as one current view requires, there would be no place on the continent where the marine fauna of the Lance could have been retained, and it must have come in from some ocean area at least a thousand miles away. In that case it is not probable that it could have been so closely related to the provincial Fox Hills fauna or that it could have escaped bringing Eocene elements with it. That a marine Cretaceous fauna could have persisted in this region after the Eocene was well advanced in the Gulf coastal plain of the United States is, to my mind, too improbable to deserve serious consideration.¹⁴

CONCLUSION

In my opinion, therefore, the conclusion is justified that the Cretaceous period did not end in the Interior Province until the sea had completely retreated from the province, and that the Lance formation should be assigned to the Cretaceous.

The final retreat of the Cretaceous Sea from the Interior Province was doubtless associated more or less closely with local orogenic movements which caused active erosion to begin or to increase in various areas; but in other areas within the province the products of this erosion were laid down as terrestrial deposits, which taken together practically bridge the gap between Cretaceous and Tertiary. The boundary between the two systems in such areas is not marked by an important break caused by general diastrophism, because the breaks and discordance and erosion

¹³ Charles Schuchert: Paleogeography of North America. Bull. Geol. Soc. Am., vol. 20, 1908, pl. 96.

¹⁴ That this hypothesis does not seem unreasonable to many of my colleagues is evident from the fact that since this paper was read before the Geological Society the United States Geological Survey has decided to classify the Lance formation, including its marine member, as Tertiary (?), although the Cretaceous affinities of its marine fauna were acknowledged by those who made the decision.

intervals in an area of continental deposition are not dependent on the same conditions that cause the major breaks in marine sediments. Even if it be true that there was a world-wide movement at the close of the Cretaceous which caused a break between marine Cretaceous and marine Eocene in all the areas where such sediments are now accessible, such a movement would not necessarily affect the accumulation of continental deposits of detrital material in an area already above sealevel, and in this case apparently it did not affect it. On the other hand, terrestrial deposits are characteristically and necessarily irregular, and the importance of breaks and unconformities in them must, therefore, be tested with great care, using all kinds of available evidence.

The Lance formation is believed to be Cretaceous on account of its intimate stratigraphic relation with the underlying marine Cretaceous, on account of the close relationship of its vertebrate and non-marine invertebrate faunas with Cretaceous faunas, and on account of the occurrence in one area of a marine Cretaceous fauna within the formation. This marine Cretaceous invertebrate fauna is held to establish the Cretaceous age of the plants which occur in the beds beneath it, in spite of the fact that these plants are said to belong to Eocene species. In other areas where the Lance formation does not include a marine member, but has a thicker development of strata, with a large vertebrate fauna of Mesozoic types, it is a fair inference that the whole formation, with its contained flora, is also of Cretaceous age. If, then, the Lance flora is in fact a Cretaceous flora, notwithstanding its close relationship with Eocene floras, it is obvious that the correlation of other formations with known Eocene formations on the evidence of fossil plants alone is open to serious question. In the case of the Denver and Arapahoe formations such a correlation is directly opposed by the evidence of the vertebrate fauna, which allies them closely with the Lance formation.

CRETACEOUS EOCENE CORRELATION IN NEW MEXICO,
WYOMING, MONTANA, ALBERTA¹

BY BARNUM BROWN

(Presented before the Paleontological Society January 1, 1914)

CONTENTS

	Page
Introduction.....	355
Hell Creek formation, Montana.....	356
Red Deer River, Alberta, Canada.....	359
Edmonton formation.....	362
Edmonton-Pierre contact.....	368
Belly River beds.....	369
Summary of the Red Deer River section.....	371
Paskapoo formation.....	371
Edmonton formation.....	373
Belly River beds.....	376
The Ojo Alamo beds.....	379
Conclusion.....	380

INTRODUCTION

For the American Museum I have been continuously engaged since June, 1900, in the exploration of the geology, flora, and fauna of three great formations which in their animal and plant life bridge over the passage from Cretaceous to Eocene time, as determined by comparison with the life of the same epochs in Europe. I propose to compare these formations with each other and with the typical Lance Creek formation of Wyoming. These formations are:

	Years
Hell Creek formation of northern Montana.....	1902-1909
Series embracing in descending order Paskapoo, Edmonton, Fort Pierre (upper), Belly River (intercalation), Fort Pierre (upper) of Red Deer River, Alberta.....	1909-1913
Ojo Alamo formation of northern New Mexico.....	1904
Lance Creek formation of Converse County, Wyoming.....	1900-1901

¹ Manuscript received by the Secretary of the Geological Society June 14, 1914.

Contribution to the symposium held by the Paleontological Society at the Princeton meeting December 31, 1913, and January 1, 1914.

In the absence of the author, presented by Doctor Osborn.

I have determined the geologic sequence in each of these formations and the succession of the species of reptiles. The mammals have been determined with the aid of Dr. W. D. Matthew, the invertebrates with the aid of Dr. T. W. Stanton, the flora with the aid of Dr. F. H. Knowlton and Dr. A. Hollick.

In this contribution to the present discussion as to what we shall consider the close of Cretaceous and opening of Eocene time in North America, I desire to add certain hitherto unpublished observations and to review observations already in print bearing on this important question.

In 1907 I published in the *American Museum Bulletin* an article on the Hell Creek beds of Montana, with lists of fauna and flora known up to that time. In 1908 and 1909 I continued work in the Hell Creek region, searching for fossils along the eastern exposure of the beds, and considerably increased the faunal list of the section.

Formations correlated with the Lance are indicated in quotation marks, thus, "Lance." It is very confusing to omit these quotation marks. The "Lance" formation should be known faunally as the TRICERATOPS ZONE. The application of the term "*Ceratops* Zone" or "*Ceratops* Beds" to this formation is absolutely erroneous and misleading because the genus *Ceratops* became extinct long before "Lance" times and is distinctive of the much more ancient Judith River or Belly River formations.

The Hell Creek and the typical Lance are the only formations which may now be absolutely correlated with each other by all the species of plants and animals which they contain. It is best, therefore, to first consider the Hell Creek.

HELL CREEK FORMATION, MONTANA

The notes on this section relate to the contact of the marine Fox Hills and the overlying "Lance" (Hell Creek beds).

Whatever the character of the Fox Hills formation may be in other localities, it is here clearly differentiated from the Pierre in lithologic structure. The partition plane separating the Fort Pierre and Fox Hills is the junction of the dark shales of the former, with the grayish-yellow sandy shales and sandstones of the latter. The formation is not extensively developed, and is here never more than 100 feet thick. It consists of arenaceous shales and soft, friable sandstones, with an increasing amount of sandstone toward the top, in marked contrast to the dark shales of the Pierre below. The sandstones are frequently rendered impure by more or less argillaceous material. In the exposures on Hell

Creek and Crooked Creek calcareous concretions similar to those of the Pierre are found in stratified planes, and the following invertebrates were taken from a concretion on Hell Creek about 20 feet below the overlying massive basal sandstone: *Cardium subquadratum* E. and S., *Nucula cancellata* M. and H., *Tellina scitula* M. and H., *Lunatia concinna* M. and H., *Scaphites conradi* Morton, and *Baculites ovatus* Say, all of which testify the marine character of the sediments at this point.

On the east fork of Crooked Creek near the old Cook ranch, on the west fork of Crooked Creek near the Gus Colin claim, and on the east fork of Hell Creek near the EE cattle camp these marine beds have been eroded in places, sometimes to a depth of 10 feet, before the succeeding massive sandstones of the fresh-water "Lance" were deposited. The strata are, however, in all cases parallel to the bedding plane of the succeeding sandstones, and the break is evidently of local erosional character.

It was observation of these local erosional breaks in the vicinity of Hell Creek that led to the statement that the beds did not represent a continuous sedimentation from the marine Fox Hills. In view of later work, this statement must be modified.

In the eastern exposures of these beds on tributaries of Big Dry, Prairie Elk, and the small streams emptying directly into the Missouri River the sandstones of the Fox Hills are finer grained, harder, and more compact. Along the eastern outcrop for a distance of nearly 30 miles and on the north side of the Missouri River these marine and brackish-water sandstones grade into the massive sandstones above without any sign of discordance.

A typical section may be seen on the east side of the Big Dry opposite the ranch-house of Mr. John Willis, 38 miles south of Glasgow, Montana. At this point there is a prominent mass of shells, *Corbula* cf. *subtriangularis*, forming a layer 4 to 8 inches thick, which was traced for a quarter of a mile.

Above this shell layer there are 20 feet of rust-red sandstones that are arbitrarily chosen as the close of the Fox Hills. These are laminated shaly sandstones, usually capped by a thin layer of flattened limonite-covered concretions that mark the point of contact with the overlying fresh-water sandstones. At another point this upper stratum of Fox Hills is a thin layer of red sandstone marked off in irregular squares, which seem to indicate a drying up of ponds, where the cracks were later filled with sand. The shaly sandstones of these upper strata are frequently spotted with radiations of a removed crystallized mineral, presumably some soluble alkaline salt, as the stone reacts for sulphates.

Through this eastern exposure I have often found it impossible to establish any definite line of demarcation between the two beds.

The insensible gradation from marine through brackish-water into fresh-water sandstones is not confined to the eastern exposures of the "Lance" on Hell Creek. The same transition is found on the border of the Lance formation on Alkali Creek, Seven Mile Creek, and Robber's Roost, all tributaries of the Cheyenne River in Weston County, Wyoming.

No sign of an angular unconformity has been noted between the Fox Hills and the "Lance," and I have never yet seen any geologic evidence of the "great diastrophic break" which is alleged to occur here.

The actual geologic history appears to be as follows: There were areas in close proximity during the close of Fox Hills times where denudation was taking place simultaneously with deposition. In the case of the nonconformity, there was a cutting off and drying up of an area without freshening before the beginning of littoral deposition; in the other case there occurred the isolation of an arm of the sea and a gradual freshening of the impounded waters before drying up.

The lithologic structure of the Hell Creek beds is similar in nearly every respect to that of the Lance of Converse and Weston counties, Wyoming. Most genera and species of vertebrates and invertebrates are common to both deposits, and the faunal facies may be considered a unit.

List of Fauna and Flora

VERTEBRATES

Mammals:

Ptilodus sp.
Meniscoëssus conquistus Cope
Meniscoëssus sp.
 Reptiles:
Triceratops serratus Marsh
Triceratops brevicornus Marsh
Triceratops sp.
Trachodon mirabilis
Trachodon annectens Marsh
Trachodon sp.
Thescelosaurus neglectus Gilmore
Ankylosaurus magniventris Brown
Palæoscincus sp.
Tyrannosaurus rex Osborn
Aublysodon sp.
Ornithomimus altus ? Lambe
Champsosaurus laramiensis Brown

Champsosaurus ambulator Brown
Brachychampsa montana Gilmore
Leidyosuchus sternbergii Gilmore
Basilemys sinuosa Riggs
 ? *Adocus lineolatus* Cope
Compsemys victa Leidy
Compsemys obscura Leidy
Helopanoplia distincta
Aspideretes sp. nov.
Aspideretes (Trionyx) foveatus Leidy
Aspideretes beecheri Hay
Scapherpeton tectum ? Cope
Diphyodus sp.
Rhineastes sp. indet.
Pappichthys sp. indet.
Scaphirhynchus
Lepisosteus occidentalis
Lamna sp.

INVERTEBRATES

<i>Unio æsopiformis</i> Whitf.	<i>Unio cylindricoides</i> Whitf.
" <i>corbiculoides</i> Whitf.	" <i>letsoni</i> Whitf.
" <i>pyramidellus</i> Whitf.	" <i>gibbosoides</i> Whitf.
" <i>verrucosiformis</i> Whitf.	" <i>pyramidatoides</i> Whitf.
" <i>retusoides</i> Whitf.	" <i>subtrigonalis</i> Whitf.
" <i>browni</i> Whitf.	<i>Sphærium planum</i> M. and H.
" <i>percorrugata</i> Whitf.	<i>Corbicula subelliptica</i> M. and H.
" <i>postbiplicata</i> Whitf.	<i>Campeloma multolineata</i> M. and H.
" <i>aldrichi</i> White	" <i>vetula</i> M. and H.
" <i>dancæ</i> White	" <i>producta</i> White
" <i>holmesiana</i> White	<i>Vivipara plicapressa</i> White
" <i>vetusta</i> Meek	<i>Cassiopella turricula</i> White
" <i>cryptorhynchus</i> White	<i>Thaumastus limmæiformis</i> White
" <i>biasopoides</i> Whitf.	<i>Bulinus rhomboideus</i> M. and H.

FLORA

<i>Equisetum lævigatum</i>	<i>Ficus spectabilis</i>
<i>Rhamnus salicifolius</i>	<i>Sequoia heerii?</i>

RED DEER RIVER, ALBERTA, CANADA

This river presents one of the finest sections for the study of Mesozoic and Eocene rocks to be seen on the continent. In a distance of approximately 300 miles, starting from the town of Red Deer, it cuts through and into sediments of four distinct formations, Paskapoo, Edmonton, Pierre, Belly River, well defined by the character of sedimentation and fossil remains.

The latest determination of these formations by the Canadian Geological Survey, 1913, is as follows:

Paskapoo	}	Laramie	}	Tertiary
Edmonton				
Fort Pierre	}	Cretaceous	}	Mesozoic
Belly River				
Fort Pierre				

The term Laramie is used by the Canadian Survey with the implied meaning given by G. M. Dawson in the "Report of Progress" for 1880-'81-'82, page 4B, as a group term to include all the stratigraphically conformable formations from the top of the Pierre-Fox Hill to the unconformity below the Oligocene.

The river canyon averages about a mile in width at the prairie level and ranges from 200 to 500 feet in depth, presenting for the most part

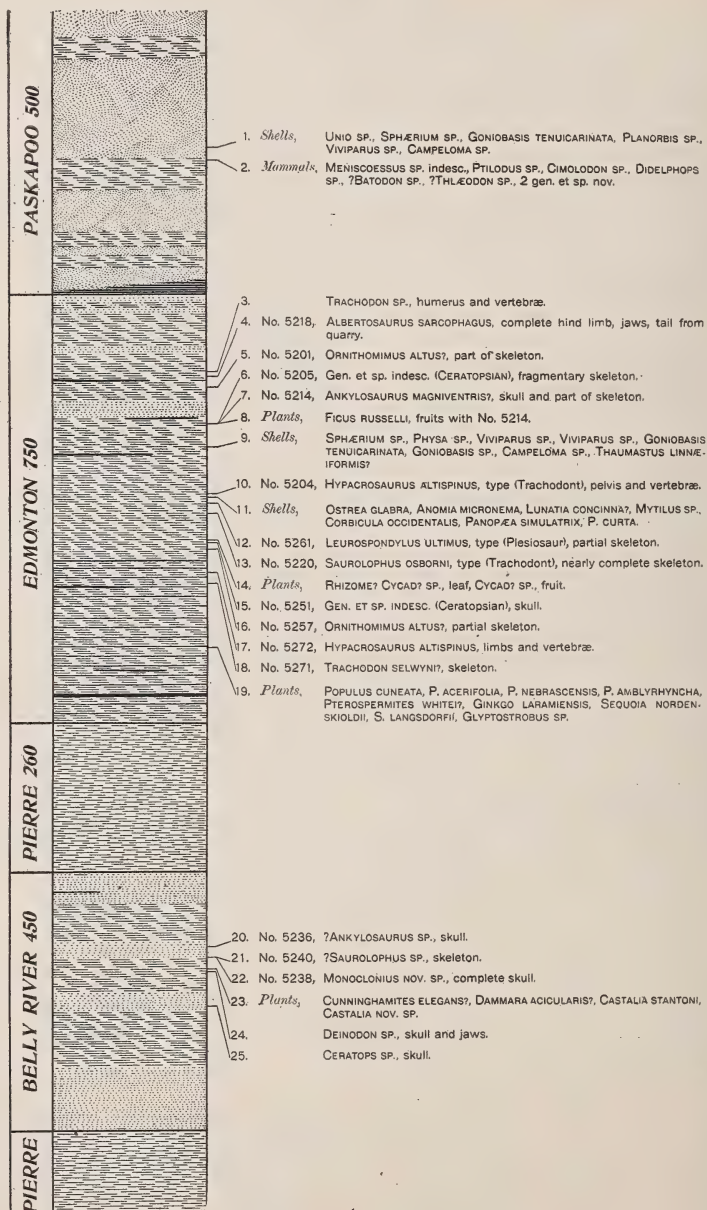


FIGURE 1.—Formations Sectioned by the Red Deer River between Red Deer and the Mouth of Sand Creek, with Location of important Fossils in the American Museum Collection.

clean-cut escarpements throughout the course examined. Pleistocene drift covers the surface of the country, and on the cut banks of the river it is usually present at the top of a given section and varies from 10 to 20 feet in depth.

In the forested section near the mountains, where the sediments are composed largely of sandstones, the river follows a rather devious course generally to the northeastward, but coming to the softer sediments of the prairie country it straightens out and follows a course generally southeastward, joining the South Saskatchewan near the fourth meridian.

The average drop of the prairie surface from Red Deer to the mouth of the Rosebud is about 13 feet to the mile, while the river falls from Red Deer to Tail Creek $5\frac{1}{2}$ feet to the mile; from Tail Creek to Willow Creek, 3 feet to the mile, and from Willow Creek to Berry Creek, about $2\frac{1}{2}$ feet to the mile. The beds dip slightly to the southwest, but are nearly horizontal; consequently the strata of each formation are exposed for long distances on either side of the river.

The Paskapoo formation, according to Mr. J. B. Tyrrell, "Geological Survey of Canada, Report of Progress" (new series), volume ii, 1887, page 135E, includes Dr. Dawson's Porcupine Hills and Willow Creek series and the upper part of his Saint Mary series, and on the Little Red Deer River the entire series attains a thickness of 5,700 feet. Near the mountains the strata lie directly on the marine Pierre, where they were deposited in a great synclinal trough, as determined by the Canadian Geological Survey. On the Red Deer River below the town of Red Deer the lowest 500 feet of these rocks are exposed. The beds are chiefly light-gray and yellowish sandstones, usually thick-bedded, frequently cross-bedded, and composed of rather coarse grains of quartz, feldspar, and mica loosely cemented together; also of light bluish-gray and olive sandy clays, frequently interstratified with bands of hard lamellar sandstone, and sometimes with layers of concretionary blue limestone. The proportion of sandstone to clay is much greater than in the underlying Edmonton formation, and the massive beds lack the coherence of the Edmonton sandstones.

At the point of contact between the hard sandstone layers and the clay underneath frequently occur clay pebbles and poorly preserved *Unio* shells representing old river channels.

Near Erickson's Landing, about 20 miles below the town of Red Deer, there is an enormous slide, the largest seen along the river, where a full section of the canyon wall 100 yards in length has slipped down to the river level. In this fallen material there are many blocks of

sandstone carrying on the lower side clay pebbles, *Unios*, and a few jaws, teeth, and bones of mammals, identified as follows:

Multituberculata:

Meniscoëssus sp. indesc.

Ptilodus sp.

Cimolodon sp.

Trituberculata:

Didelphops sp.

? *Batodon* sp.

? *Thlæodon* sp.

? Gen. indesc.

? Gen. indesc.

Pantolestidæ gen. indet.

? Creodonta

? Taligrada

} ? Marsupiala

} ? Insectivora

The Multituberculates and Trituberculates are unmistakably those of the Lance, but the placental mammals have not been found in the Lance and appear to belong to the Paleocene groups of mammals, although they do not compare closely with Puerco or Torrejon genera. This layer was located in the bluff at a point 150 feet above the river. Apparently it was a local deposit, an old river channel of the Paskapoo period which crossed the present river at right angles. Twenty-five feet above the mammal stratum there is a bed of shells 8 inches thick from which Dr. T. W. Stanton has identified *Unio* sp., *Sphærium* sp., *Gonio-basis tenuicarinata* M. and H., *Planorbis* sp., *Viviparus* sp., *Campeloma* sp., which he says are suggestive of Fort Union rather than earlier forms.

From Gaetz Valley for a distance of 3 miles appears, first on one side, then on the other, a nearly perpendicular cliff of massive brownish sandstone nearly 100 feet high in places. It is composed of loosely cemented rounded grains of quartz and feldspar, with a few lenses of harder concretionary sandstone usually capping pillars of the softer sandstone underneath. This sandstone overlies the lignite and belongs to the Paskapoo series. It does not appear to contain fossils.

EDMONTON FORMATION

Near the middle of range XXIV the first large coal seam appears on the right bank at the water level. "This seam occupies the same geological position as the big coal seam on the Saskatchewan River farther north, namely, the top of the clays and sandstones of the Edmonton subdivision of the Laramie, and it is not improbable that it is a continuation of the

same seam" (Tyrrell: Annual Report Canadian Geological Survey, volume ii, page 61E (new series), 1886). Where first seen it is from 4 to 6 feet thick, impure in quality, and is composed of layers of pure coal separated by bands of clay and shale. At this point it is bedded on an uneven surface of rust-brown sandstone and gravel. It is exposed for 400 yards downstream, where it disappears or dips under the tree-covered bank. For the next few miles it appears first on one side, then on the opposite side, wherever there is a cut bank. About 5 miles upstream from the present crossing of the Grand Trunk Railroad the big vein is about 18 feet thick where exposed on the north bank. This coal vein, on account of its widespread distribution separating as it does strata of markedly different character and different faunæ, is considered by Tyrrell to be the upper limit of the Cretaceous strata, an opinion in which I concur. But the underlying Cretaceous rocks are, as I shall show later by the vertebrate fossils, older than before suspected.

Under the big vein several thinner coal seams appear at intervals and the intervening sediments change rapidly in character. In color they are much lighter than the olive shales above; in some places

Horizontal scale: 3 millimeters = 1 mile

Vertical scale: 1 millimeter = 20 feet

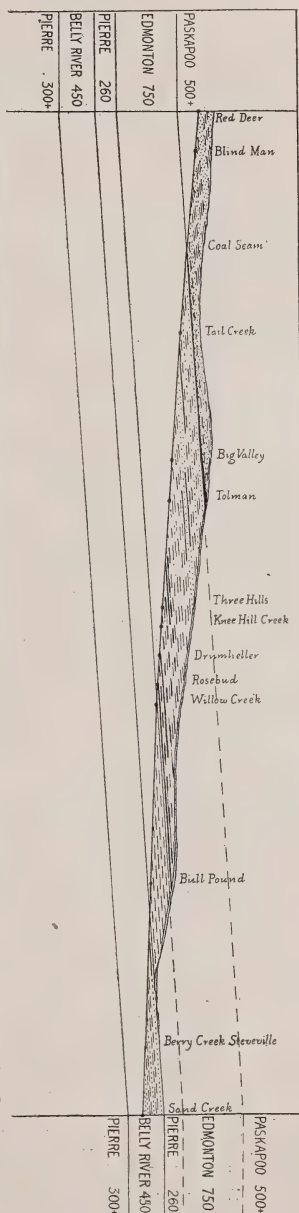
Glacial drift = double line

Average erosion of bluff, $13\frac{1}{2}$ feet to the mile

Average fall of Red Deer River between Tail Creek and Willow Creek, 3 feet to the mile

Average fall of Red Deer River between Willow Creek and Berry Creek, $2\frac{1}{2}$ feet to the mile

FIGURE 2.—Horizontal Section of Red Deer River Canyon between Red Deer and Mouth of Sand Creek



almost white. No massive sandstones characteristic of the Paskapoo series were seen under the thick coal vein.

At a point about $1\frac{1}{2}$ miles below the Grand Trunk Railroad bridge the river cuts through a nearly white sandy clay filled with glistening particles of mica. This stratum is very homogeneous and weathers in vertical faces. It continues down the river several miles, and in the valley of Tail Creek forms the conspicuous white band near the top of the formation.

Below this conspicuous white layer the beds are as a whole lighter than those above the big coal vein and are distinctly banded in light colored sandy-clay strata, thin coal seams, and carbonaceous clays.

The first dinosaur bones, a humerus and vertebrae of *Trachodon* sp., were found at water level 1 mile above the wagon bridge across the Red Deer River at the mouth of Tail Creek. This is the highest level in the Edmonton beds in which dinosaur bones were found, approximately 100 feet below the big coal seam that marks the top of the formation.

For several miles below this point there is little appreciable change in the character of the beds; talus and brush obscure most of the banks and clean-cut escarpments are seen only in bends of the river.

About 30 miles below Tail Creek opposite the mouth of Big Valley occurs the most rugged exposure of this formation along the river. Here on the west side for a distance of a mile the beds are eroded into bad lands that extend a mile back from the river. The beds are composed chiefly of clays, with sandstone layers toward the top, and are distinctly banded light and dark toward the top and light blue-gray at the base, with an occasional thin seam of ironstone that weathers to a rust-brown color. The prairie level is 470 feet above the river, and no less than 50 feet of the upper strata seen at Tail Creek, including the big coal seam and some of the white sandstone layers, are missing.

A generalized section taken at the lower end of the bad lands, not the highest point, shows as follows:

	Feet
Boulder-clay	10
Loosely cemented white sandstone and clay.....	40
Impure lignite.....	1
Light clay.....	10
Lignite	3
Clay, dark gray.....	20
Lignite	1
Sandy clay, light gray above, darker below.....	25
Impure lignite and carbonaceous clay.....	6
White sandy clay.....	20
Brown-gray clay with ironstone.....	40

	Feet
Sandy white clay.....	15
Hard laminated sandstone, generally persistent.....	4
Light clay, occasional sandstones.....	100
Laminated reddish sandstone, fossils numerous.....	5
Clay and iron-encrusted pebbles, fossils numerous.....	30
Sandstone	8
Light blue-gray clay.....	70
	408

Many vertebrate fossils were collected at Big Valley, ranging from near the top to the bottom of the exposures. In the upper 50 feet of sandstone a few vertebræ of *Champsosaurus* sp., an occipital condyle of a crocodile, and fragments of a Trionychid turtle were secured, the only representatives of those families seen in the Edmonton formation, with exception of one Trionychid turtle collected near the bottom of the beds at Willow Creek.

The following invertebrates were secured from a stratum about 100 feet above the river: *Sphærium* sp., *Physa* sp., *Viviparus* sp. related to *V. raynoldsanus* M. and H., *Viviparus* sp. related to *V. prudentius* White, *Goniobasis tenuicarinata* M. and H., *Goniobasis tenuicarinata* var., *Goniobasis* sp., *Campeoloma* sp., *Thaumastus linnæiformis* M. and H.? In his comments Dr. T. W. Stanton says that "there is nothing characteristic of either Lance or Judith River in this lot and some of the forms are more suggestive of Fort Union."

Below Big Valley the banks are clean scarped and the beds continue of similar character for several miles. A workable seam of lignite, about 3 feet thick, appears near the top of the bank 3 miles below the mouth of Big Valley and a seam, probably the same one, appears again just above Tolman Ferry. The upper part of the beds continues banded in light and dark color, with white argillaceous sandstones interstratified with impure lignite and carbonaceous clays. Iron-encrusted sandstone lenses increase toward the base and the lower strata are composed chiefly of light gray clays.

From Big Valley down to the end of the formation the upper strata disappear about as rapidly as the fall of the river brings the lower strata to view, so there is no great variation in the height of the banks. Not less than 200 feet of the upper strata have been eroded at Tolman, where the canyon walls are estimated to be 300 feet high.

Throughout the Edmonton formation water ripple-marked sandstones are common. At a point 2 miles above Tolman Ferry on the left bank there is a bed 100 yards square, and in which four successive series of

ripples are preserved one above the other. Each series was evidently formed by currents coming to the shoreline from a different angle, as no two are parallel. On one of these slabs collected there are worm tracks and several impressions of a horsetail rush, identified by Dr. A. Hollick as *Equisetum* sp. nov.

One and one-half miles above Tolman, at a point 190 feet above the river, a skull and partial skeleton of *Ankylosaurus* was collected, and with it were associated several fruits, identified by Dr. F. H. Knowlton as *Ficus russelli*. At this same station several poorly preserved plant remains were secured from a hard argillaceous sandstone at the water level. They are identified by Dr. A. Hollick as a rhizome ?, possibly of an aquatic plant, Cycad ? sp., a leaf, and Cycad ? sp., a fruit, but are not diagnostic of the age of the beds.

Below Tolman for 16 miles there is little appreciable change in the appearance of the beds, which are chiefly clay; local strata of hard sandstones appear and disappear in a short distance, and in two or three places there are beds, unmistakably, of stream channels. One particularly noticeable is seen at water level 3 miles above Tolman and another at a point capping the section 16 miles below Tolman.

Four miles below Tolman on the right bank, at a point 100 feet above the river, there is a conspicuous bed of shells: *Anomia micronema* Meek, *Corbicula occidentalis* M. and H., *Panopaea simulatrix* Whiteaves, *Panopaea curta* Whiteaves, all brackish-water forms, associated with broken shells of *Ostrea* sp. This shell bed appears again 6 miles below Tolman on the left bank, about 110 feet above the river, and 1 mile farther down the river, where shells, *Corbicula occidentalis*, form a solid bed 18 inches thick.

At Stauffer's, 16 miles below Tolman on the left bank, there is a bed of *Ostrea* sp. 2 feet thick in approximately this same horizon. The same oyster-bed appears at the head of Fox Coulee, 1 mile from Munson, in the cut of the Canadian Pacific Railroad, 20 feet below the prairie level, where the following shells were collected: *Ostrea glabra* M. and H., *Anomia* sp., *Mytilus* sp., *Lunatia concinna* M. and H. ?, all brackish-water and marine Cretaceous types that are common to the Judith River and the base of the Lance.

The stations represented by these four lots of shells do not vary 25 feet above or below a horizontal plane, and I think they are on the same level.

A Plesiosaur skeleton, which I have described under the name *Leiospondylus ultimus*, was found in approximately the same stratum, 6 miles below Tolman on the left bank, 120 feet above the river. This specimen is interesting chiefly because it extends the history of the group of Meso-

zoic marine vertebrates considerably later in time than any heretofore recorded. In the same level, close by, was found a fragmentary skull of a Ceratopsian, number 5259, soon to be described as the paratype of a new genus.

About 14 miles below Tolman another prominent coal seam comes to view at water level, but does not continue downstream more than a mile. Carbonaceous layers are, however, more numerous and the exposures become in consequence darker in appearance. Iron-encrusted lenses and pebbles also increase in number, uniform layers frequently extending long distances. There is a greater amount of ironstone and evidently more plant remains in the lower part of the beds from here down to the Pierre and the clays become more and more shaly. Limbs and sections of trees usually encrusted by chalcedony, with brilliant quartz crystals at points of fracture, are abundant, though the mass of vegetal material is poorly preserved.

Near the home of Mr. Simpson, on the left bank, 20 feet above the river and almost opposite the mouth of Kneehills Creek, there is a bed of leaves from which several well preserved specimens were secured. They are identified as follows: *Populus cuneata* Newb., *Populus acerifolia* Newb., *Populus nebrascensis* Newb., *Populus amblyrhyncha* Ward, *Pterospermites* prob. *Whitei* Ward, *Ginkgo laramiensis* Ward, *Sequoia nordenskioldii* Heer, *Sequoia langsdorfii* (Brgh.) Heer, *Glyptostrobus* sp.

After examination of the plants collected in 1911—that is, *Sequoia nordenskioldii*, *S. langsdorfii*, *Glyptostrobus* ? sp., *Pterospermites* prob. *Whitei*, and *Populus cuneata*—Dr. Knowlton reports that “the species indicate beyond all manner of question or doubt that the age is Fort Union.” Additional better material was secured from the same spot in 1912, and the species enumerated in the complete list above were determined by Doctor Hollick, who says that “the specimens from the Edmonton formation (near Simpson’s house, opposite mouth of Kneehills Creek, etcetera) indicate, unquestionably, the Fort Union age of this horizon.”

The position of this plant layer in the Edmonton beds is not less than 250 feet below the *Ostrea* layer, in which the Plesiosaur skeleton *Leurospondylus* was collected. The definite location of these horizons is most important, for whereas the age of the land reptiles has been considered debatable, the marine reptiles are clearly of Mesozoic age, and the same species of land reptiles are found above and below the marine forms. From the vertebrate and invertebrate remains it seems very clear that these rocks are not of Fort Union age, but as shown by the plants the climatic conditions of Fort Union time were long foreshadowed toward the close of the Cretaceous.

From Kneehills to the end of the formation there is no marked lithologic change. The beds are chiefly shaly clays, alternating with indurated sands and pronounced dark carbonaceous layers. There are many lignite seams of good quality, several of which are mined at Drumheller, near the mouth of Michichi Creek and at the mouth of the Rosebud. One large seam, which apparently continues over a large area, is prominent below the mouth of the Rosebud on the left bank. One mile below the mouth of the Rosebud it has been burned, and the clays above and below to a depth of 50 feet indurated sufficiently to resist erosion, so that brilliant vermilion cliffs stand out in front of the somber background. Four miles below the mouth of the Rosebud this seam measures over 6 feet in thickness where it is approximately 100 feet above the Pierre.

EDMONTON-PIERRE CONTACT

Twelve miles below the Rosebud a small stream—Willow or Saule Creek—joins the Red Deer from the east. Many fine sections, showing the contact of the Edmonton and Pierre, appear near the junction of these two streams.

The first unmistakable marine beds containing fragments of *Ammonites* sp., *Scaphites* sp. were observed 1 mile above the mouth of Willow Creek. The clay-shales of these beds are thin, finely laminated layers from one-half inch to 3 inches thick, interstratified with seams of ocher, and vary from buff to a deep coffee color, the colors alternating with one another. Above the shales and *conformably overlying* them in all observed points of contact are 50 feet of light, almost white, sandy clays, sometimes cross-bedded and interstratified with layers of dark carbonaceous clays. Selinite crystals occur all through these strata. The overlying sandy clays mark the transition from purely marine to brackish-water beds. In them frequently occur beds of oysters and considerable wood. At the mouth of Willow Creek, in the bluffs back of the home of Mr. J. H. Caldwell and 50 feet above the coffee-colored shales, I collected the following shells: *Ostrea subtrigonalis* E and S., *Ostrea glabra* M. and H.? Doctor Stanton comments on this lot: "These two species are found in both Judith River and Lance formations." Near by in the same horizon were the remains of a Trionichid turtle.

The Edmonton formation differs greatly in lithologic character from the Fox Hills, which occupies the same relative position in the United States where it is a sandstone formation, but I believe it to have been, in part at least, synchronous with the Fox Hills. It may possibly be correlated with the Laramie, according to its original definition.

The following section was taken 3 miles below the mouth of Willow Creek:

	Feet
Glacial boulders and yellowish fine-grained Pleistocene (?) silt unconformably overlying beds below.....	30
Light slate-colored clay.....	20
Dark carbonaceous clay.....	4
Lignite	1
Gray-white sandy clay.....	8
Ocherous yellow clay.....	15
Carbonaceous material.....	2
White indurated sand, some concretions.....	15
Coffee-colored fine-lined Pierre shale.....	50
	145

The upper 30 feet of material in this section is a fine-grained yellowish sandy silt, non-fossiliferous and without lines of stratification. It unconformably overlies the beds below and varies from a few feet to 50 feet in thickness, and is present in most sections. In the upper part there are frequently glacial boulders and gravel. This material may have been derived from the Miocene rocks of the Hand Hills during Pleistocene times.

The coffee-colored Pierre shales are about 100 feet thick and continue down the river as far as Dorothy, where dark slate-colored shales appear below similar to the typical Pierre shales of the United States. Fragmentary *Ammonites*, *Scaphites*, wood, and occasionally fish bones were seen in these strata.

The Pierre shales are seen along the river for a distance of nearly 30 miles below Willow Creek, with clean-cut escarpments in the bends of the river, though the banks are mostly sloping and grass-covered.

BELLY RIVER BEDS

Near Fieldholme, the old Marquis of Lorne Crossing, about 6 miles below the mouth of Bullpound Creek, a new series, the Belly River beds, appear underlying the marine Pierre. This is distinctly a fresh and brackish-water series composed chiefly of soft sandstones and clays. Vegetal matter is less abundant than in the Edmonton formation and there are few beds of lignite. The sedimentation of the Belly River beds is exactly comparable to that of the Judith River beds with one exception—the false or cross-bedding is much more pronounced throughout the Judith River area.

The first stratum recognized was seen on the left bank of the river, a

light-gray sandy clay layer 4 feet thick overlying a seam of impure lignite $1\frac{1}{2}$ feet thick. Twelve miles below Fieldholme, in the big bend of the Red Deer, where it again turns east, a thick vein of lignite, probably the same one noted above, appears on the left bank. At this point the full section of the cut-bank is composed of Belly River beds capped by glacial gravel and large boulders. The overlying Pierre entirely disappears near Matjiwin Creek. Below this point the banks of the river gradually increase in height, and at the mouth of Berry Creek, near Steveville, are eroded back into the prairie in picturesque bad lands on either side of the river. At water level, on the left bank 100 yards above the ferry at Steveville, there is a compact ledge of sandstone in which plant remains are well preserved. The following species were collected from this ledge: *Dammara* sp., possibly *D. acicularis* Knowlton, *Castalia stantoni* Knowlton, *Castalia* sp. nov., *Aspidium* sp. Dr. A. Hollick identified these fossils, and says that "the specimens from the Belly River formation (Steveville, Alta., etcetera) are nearly all species which are typical of the Judith River formation and indicate the stratigraphic identify of these two formation." Extensive bad lands continue down the river as far as the mouth of Sand Creek, 12 miles below Steveville, where the banks are about 300 feet in height.

Below Sand Creek for 15 miles, in what is known as "Dead Lodge Canyon," the banks gradually decrease in height and near the end of this course become sloping and grass-covered. A few clean-scarped exposures again appear near the ranch-house of Mr. M. J. Stapleton, in section 15, range IX, township 22, where the lower strata of the Belly River beds are composed chiefly of compact yellowish indurated sand and lamellar sandstones. In this yellow compact sand, 1 mile below Stapleton's, I collected a nearly complete skull of *Monoclonius* sp. The lower sand strata exposed on the Red Deer River closely resembles the lower part of the Belly River series exposed on the Belly River at Big Island, 12 miles below Lethbridge, described by Dawson in *Canadian Geological Survey, Report of Progress, 1882-'83-'84*, pages 73-74C.

The upper strata of the few clean-scarped exposures near the mouth of Blood Indian Creek contain *Baculites* sp. and *Scaphites* sp., and undoubtedly belong to the Pierre. The lower 50 feet are composed chiefly of yellowish sand and sandstone, the base of the Belly River series. Below Blood Indian Creek the banks are mostly sloping and grass-covered, with few exposures, which are said by McConnell to be chiefly yellowish sand and sandstones, representing the base of the Belly River series, which are exposed at intervals down to a point 25 miles west of the confluence of the Red Deer River with the South Saskatchewan.

Beyond these determinable exposures the sloping banks are grass-covered, and below the forks of the river the underlying Pierre appears.

SUMMARY OF THE RED DEER RIVER SECTION

PASKAPOO FORMATION

The Paskapoo beds consist of more or less hard, light gray, or yellowish sandstones, usually thick-bedded and sometimes cross-bedded; also of light bluish-gray and olive shales, often interstratified with bands of concretionary blue limestone. It is essentially a sandstone formation.

The strata are purely of fresh water and eolean origin.

Near the mountains these beds, according to Tyrrell, appear to rest conformably on the Pierre shales. On the Red Deer River and elsewhere they are separated from the underlying brackish-water Edmonton beds by a widely distributed coal seam of varying thickness. No other sign of unconformity has been recognized, but a considerable time elapsed between the close of the Edmonton and the beginning of the Paskapoo—a time interval represented by all or the greater part of the Lance. No dinosaurs are found in these beds, and the abundant and varied dinosaurs of the underlying Edmonton formation are an older facies than those of the Lance.

Before the sedimentation began the entire group of dinosaurs had become extinct. A mammalian fauna now takes its place. This fauna is more varied than that of the Lance and is comparable to it, according to Dr. Matthew.

The invertebrates are all fresh-water species. Eocene climatic conditions had by this time become well established, as shown by the varied species of plant life.

VERTEBRATES

Multituberculata :

Meniscæssus sp. indesc.

Ptilodus sp.

Cimolodon sp.

Trituberculata :

Didelphops sp.

? *Batodon* sp.

? *Thlæodon* sp.

? Gen. indesc.

? Gen. indesc.

Pantolestidæ gen. indet.

? *Creodonta*

? *Taligrada*

} ? Marsupiala

} ? Insectivora

In the lists of plants accredited to this formation by Tyrrell and Penhallow some errors may have been made in determination and location of horizons, so I have given them separately.

INVERTEBRATES

Red Deer American Museum Collec- tion	Red Deer River and elsewhere listed by Tyrrell
<i>Unio</i> sp.	<i>Unio</i> Danae M. and H.
<i>Sphaerium</i> sp.	<i>Sphaerium formosum</i> var.
<i>Goniobasis tenuicarinata</i> M. and H.	<i>Limnaea tenuicosta</i> M. and H.
<i>Planorbis</i> sp.	<i>Physa copei</i> White.
<i>Viviparus</i> sp.	<i>Acroloxus radiatulus</i> Whiteaves
<i>Campeloma</i> sp.	<i>Thaumatococcus limnaea formis</i> M. and H.
	<i>Goniobasis tenuicarinata</i> M. and H.
	<i>Hydrobia</i> sp.
	<i>Campeloma producta</i> White
	<i>Viviparus Leai</i> M. and H.
	<i>Valvata filosa</i> Whiteaves
	<i>Valvata bicincta</i> Whiteaves.

PLANTS

List published by Tyrrell for entire series of Paskapoo specimens identified by Sir William Dawson

<i>Onoclea sensibilis</i> Linn	<i>Populus arctica</i> Heer
<i>Sequoia nordenskioldii</i> Heer	<i>Ficus</i> sp.
<i>Sequoia langsdorffii</i> Heer	<i>Salix laramiana</i> Dawson
<i>Sequoia conttsiae</i> Heer	<i>Viburnum asperum</i> Newb.
<i>Taxodium occidentale</i> Newb.	<i>Viburnum saskatchnense</i> Dawson
<i>Platanus nobilis</i> Newb.	<i>Catalpa crassifolia</i> Newb.
<i>Corylus macquarrii</i> Heer	<i>Sapindus</i> sp.
<i>Quercus</i> sp.	<i>Carya antiquorum</i> Newb.
<i>Populus acerifolia</i> Newb.	<i>Juglans</i> sp.
<i>Populus richardsoni</i> ? Heer	<i>Nelumbium saskatchnense</i> Dawson

To this list Sir William Dawson added a year later:

<i>Podocarpites tyrrellii</i> Dawson	<i>Populus nervosa</i> ? Newb.
<i>Populus genetrix</i> Newb.	<i>Trapa borealis</i> Heer.

Complete list from Red Deer region published by D. P. Penhallow, Department of Mines, Canadian Geological Survey Report Number 1013, pages 14-15, 1908

<i>Almites grandifolia</i> Newb.	<i>Cornus rhamnifolia</i> O. Web.
<i>Carya antiquorum</i> Newb.	<i>Corylus americana fossilis</i> Newb.
<i>Catalpa crassifolia</i> Newb.	<i>Corylus macquarrii</i> (Forbes) Heer
<i>Cercis parvifolia</i> Lesq.	<i>Equisetum arcticum</i> Heer
<i>Clintonia oblongifolia</i> Penh.	<i>Ficus</i> sp.

<i>Glyptostrobus europæus</i> (Brongn.) Heer	<i>Quercus ellisiana</i> Lesq.
<i>Juglaus</i> sp.	<i>Quercus</i> sp.
<i>Juglaus acuminata</i> A. Br.	<i>Quercus ellisiana</i> Lesq.
<i>Juglaus laurifolia</i> Knowlton	<i>Salix laramiana</i> Dawson
<i>Juglaus leconteana</i> Lesq.	<i>Sapindus</i> sp.
<i>Juglaus occidentalis</i> Newb.	<i>Sequoia conttsiæ</i> Heer
<i>Lastrea fischeri</i> Heer	<i>Sequoia langsdorffii</i> (Brongn.) Heer
<i>Maiantherium grandifolium</i> Penh.	<i>Sequoia nordenskioldii</i> Heer
<i>Nelumbium saskatchnense</i> Dawson	<i>Sphenopteris blæmstrandii</i> Heer
<i>Osmunda macrophylla</i> Penh.	<i>Sphenopteris guyotti</i> Lesq.
<i>Phyllites carneosus</i> Newb.	<i>Sphenoxamites oblanceolatus</i> Penh.
<i>Populus acerifolia</i> Newb.	<i>Taxodium distichum miocenium</i> Heer
<i>Populus arctica</i> Heer	<i>Taxodium occidentale</i> Newb.
<i>Populus cuneata</i> Newb.	<i>Typha</i> sp.
<i>Populus daphnogenoides</i> Ward	<i>Viburnum ovatum</i> n. sp.
<i>Populus obtrita</i> Dawson	<i>Viburnum asperum</i> Newb.
<i>Populus richardsoni</i> Heer	<i>Viburnum saskatchnense</i> Dawson.

EDMONTON FORMATION

The terms Upper and Lower Edmonton should not be employed, for the formation is lithologically and faunistically an indivisible unit. The terms were originally used by the present writer as a check on the location of fossils. When the entire series of beds were closely examined it was found that such distinction was not warranted.

The Edmonton formation consists chiefly of siliceous clays interstratified with seams of lignite and thin strata of whitish sandstones. It is essentially a lignite formation.

The strata are of marine and brackish-water origin and everywhere *conformably* overlie the marine beds below. The whole series shows an uninterrupted successive sedimentation from purely marine conditions at the base through brackish-water during most of the period, with a gradual freshening toward the top.

This formation fulfills the original definition of the term Laramie.

Vertebrate remains are abundant. Neither mammalian nor fish remains have been recorded.

One turtle has been found at the base of the beds, and a turtle associated with a rhynchocephalian and a crocodile were found near the top of the formation. These are semi-aquatic forms, and their remains would be expected in sediments deposited chiefly in water, but they are noticeably absent. It is evident that the environment was not suitable to such forms. Marine vertebrates (plesiosaurs) are found as high as the middle of the beds.

Dinosaurs are found in great numbers from near the top to the bottom of the beds, and the same species occur throughout the formation. The remains occur as individual skeletons and partial skeletons, but are frequently massed together in great numbers as separate bones and partial skeletons. The bones are silicified and frequently they are filled with calcite.

The vertebrate fauna is distinct from that of the Lance and few species are common to the two formations. Most of the Edmonton genera are structurally more primitive than those of the Lance and several genera not found in the Lance are common to the Judith River. The faunal facies, as a whole, is intermediate, but closer to that of the Judith River formation than to the Lance.

Trachodonts are most numerous of all the dinosaurs in this formation. All are papillate-toothed species. Three well defined genera—*Trachodon*, *Saurolophus*, and *Hypacrosaurus*—are known. Of these *Trachodon* ranges from the Belly River beds through the Edmonton and to the close of the Lance, but the Lance species, *T. mirabilis* and *T. annectens*, have not been recorded. *Hypacrosaurus* occurs in the Belly River and *Saurolophus*, or a closely related genus, occurs there also.

Ceratopsians are comparatively rare and are represented by a large form of primitive skull structure and a small aberrant form, neither of which has been described. The characteristic genus, *Triceratops*, and its less abundant contemporary, *Torosaurus* of the Lance, do not occur in the Edmonton.

Armored dinosaurs are somewhat more numerous than the Ceratopsia. The Lance genus and species *Ankylosaurus magniventris* occurs in this formation and *A. tutus* is found in the Belly River. An allied genus, not yet described, is common to this formation and to the Belly River, but does not occur in the Lance. *Palaeoscincus*, another related genus, occurs in the Belly River and in the Lance, but has not been recorded in the Edmonton.

Carnivorous dinosaurs are as numerous as the armored forms. *Tyrannosaurus* of the Lance does not occur, but a common form about one half as large and ancestral to it is *Albertosaurus sarcophagus*. *Ornithomimus altus* is a Belly River species which occurs here and has also been noted in the Lance.

The dinosaur fauna forms a series of successive genera, the phyletic relationship of which is determined by the evolutionary development of skeletal parts, and there is no break in this series from its first appearance low down in the Cretaceous to the final disappearance of the entire group in what we propose to call the close of the Cretaceous.

The invertebrates corroborate the testimony of the vertebrates. The identifications were made by Dr. T. W. Stanton, whose comments are as follows:

"I have recently examined your invertebrates from the Edmonton and Paskapoo formations of Alberta. Those which you have already sent from the Edmonton beds include several lots composed of brackish-water shells, with a slighter mixture of marine forms (*Lunatia*) and several lots of purely fresh-water shells. The brackish-water collections are certainly Cretaceous, and consist of species which all occur either in identical or very closely related forms in both the Judith River and in the brackish-water bed, which occurs at the top of the Fox Hills and the base of the Lance.

"The fresh-water collections contain no species characteristic of either the Judith River or the Lance, and while some of them, like *Goniobasis tenuicarinata*, occur in the Lance, the general aspect of the fossils is somewhat more suggestive of the Fort Union species as occurring in the Belly River beds of Alberta, and it may be that more of these types than we have supposed range down as low as the Judith River."

The plant remains from this formation, though not extensive, are nevertheless of considerable importance. Practically all of the described species were made known from later deposits, and few if any of the species have been found in earlier deposits. The paleobotanists (Dr. F. H. Knowlton and Dr. A. Hollick) who have examined this collection are of one opinion that the plants are of Fort Union age. The Edmonton beds are practically horizontal, and the stratum containing all but one of the identified species of plants lies 250 feet below that in which plesiosaurs (animals of accepted Mesozoic age) occur.

It seems not impossible to reconcile the evidence of the flora with that of the fauna. The location of the plants is positive and the determination admitted, but their significance has probably been misinterpreted.

Lesquereaux, in the study of Cretaceous floras, long ago expressed the opinion "that groups of identical fossils, especially vegetable ones, do not prove or indicate contemporaneity of the formations which they characterize when these formations are observed at great distances or under different degrees of latitude."

In this upper part of the Cretaceous called into question by the presence of Eocene plants it is probable that Eocene climatic conditions had already begun. During the close of the Cretaceous and the beginning of the Tertiary there was a long period of equable climate, and it is evident that the flora was temperate and of wide-spread distribution. For these very good reasons the plant remains do not prove whether widely separated beds that contain the same species are strictly contemporaneous or successive.

VERTEBRATES

Red Deer River, American Museum Collection

<i>Saurolophus osborni</i> Brown	<i>Albertosaurus sarcophagus</i> Osborn
<i>Hypacrosaurus altispinus</i> Brown	<i>Ornithomimus ? altus</i> Lambe
<i>Trachodon</i> sp.	" sp.
<i>Certopsia</i> gen. et sp. nov.	<i>Leurospondylus ultimus</i> Brown
" gen. et sp. nov.	<i>Champsosaurus</i> sp.
<i>Ankylosaurus magniventris</i> Brown	Trionychidæ
Ankylosauridæ gen. et sp. nov.	Crocodylia
" sp.	

INVERTEBRATES

Red Deer River, American Museum Collection

<i>Sphaerium</i> sp.	<i>Unio</i> sp., related to <i>Unio danæ</i> M. and H.
<i>Physa</i> sp.	
<i>Viviparus</i> sp., related to <i>V. raynoldanus</i> M. and H.	<i>Ostrea glabra</i> M. and H.
<i>Viviparus</i> sp., related to <i>V. prudentius</i> White	<i>Ostrea subtrigonalis</i> E. and S.
<i>Viviparus</i> sp., probably undescribed	<i>Anomia micronema</i> Meek
<i>Goniobasis tenuicarinata</i> M. and H.	<i>Mytilus</i> sp.
<i>Goniobasis</i> " var.	<i>Corbicula occidentalis</i> M. and H.
<i>Goniobasis</i> sp.	<i>Corbicula cytheriformis</i> M. and H.
<i>Campeloma</i> sp.	<i>Panopsæa simulatrix</i> Whiteaves
<i>Thaumastus limnæiformis</i> M. and H.	<i>Panopæa curta</i> Whiteaves
	<i>Lunatia concinna</i> M. and H.

PLANTS

Red Deer River, American Museum Collection

<i>Populus cuneata</i> Newb.	<i>Glyptostrobus</i> sp.
<i>Populus acerifolia</i> Newb.	<i>Carpites</i> cf. <i>C. lineatus</i> Newb.
<i>Populus nebrascensis</i> Newb.	Pterospermites prob. <i>P. Whitei</i> Ward
<i>Populus amblyrhyncha</i> Ward.	<i>Equisetum</i> sp. nov.
<i>Ginkgo laramiensis</i> Ward	<i>Ficus russelli</i> Knowlton
<i>Sequoia nordenskioldii</i> Heer	Cycad ? sp.
<i>Sequoia langsdorfii</i> (Brgh.) Heer	

Other species accredited to this formation by Tyrrell:

<i>Trapa borealis</i> Heer	<i>Salisburia</i> sp.
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BELLY RIVER BEDS

This series consists of light-gray clays and soft whitish sandstones interbedded with ironstone-encrusted pebbles in the upper two-thirds of the formation and soft yellowish, massive sandstones at the base.

The beds are chiefly of fresh-water origin and appear to be a continuation of the Judith River Beds.

Cross-bedding is less frequent and sedimentation took place under quieter and more uniform conditions than in the Judith River Beds.

Only two or three local beds of lignite of inferior quality appear in the upper part of these beds on the Red Deer River and vegetal remains are less common than in the Edmonton.

Fossil remains are more abundant than in any of the Cretaceous formations and the dinosaurs are more varied in genera and species than in earlier or later formations. The dinosaurs are distinctly more primitive than those of the Lance, but there is no change in facies. This is conclusively demonstrated in those families adequately known from both formations, such as *Deinodontidæ*, *Ceratopsidæ*, *Trachodontidæ*, and *Ankylosauridæ*.

While there is a marked contrast between different genera that do not run through, several in the Lance are clearly derivable from Belly River genera through intermediate forms in the Edmonton.

In the *Deinodontidæ* *Deinodon* of the Belly River, *Albertosaurus* of the Edmonton, and *Tyrannosaurus* of the Lance form a phylogenetic series.

In the *Ceratopsidæ* the phyla are not so clear, but it seems probable that *Triceratops* of the Lance was derived from *Ceratops* of the Belly River through a known but not yet described genus of the Edmonton.

The *Trachodontidæ* may now be divided into two groups which share in common a ducklike bill.

In the first group the skull is without ornamentation, pelvis with ischium terminating in a blunt rounded point. *Trachodon*, typical of this group, ranges through the Belly River, Edmonton, and Lance. Closely related to it is the genus *Kritosaurus*, which is known only from the Belly River Beds and the Ojo Alamo Beds.

In the second group the skull is ornamented by a crest; pelvis with ischium terminating in a large footlike end. This group is not known to occur in the Lance, but three genera are now known from lower horizons.

Hypacrosaurus occurs in the Edmonton; also in the Belly River. *Sauroplophus* occurs in the Edmonton, and a closely related genus not yet described is at present known only from the Belly River.

In the *Ankylosauridæ* the genus *Ankylosaurus* passes through the Belly River, the Edmonton, and the Lance. A closely related genus not yet described occurs in the Belly River and the Edmonton, but is not known from the Lance.

In the *Ornithomimidæ* *Ornithomimus* passes directly through the Belly River, Edmonton, and Lance.

The invertebrates and plants are determined unquestionably of Judith

River age, and the plants are said to have very little affinity with the flora of the Lance or Fort Union.

The vertebrates, on the other hand, are of Judith River age and are beyond question closely related and in most genera and species directly ancestral to those of the Edmonton and Lance.

Many of the genera and species of dinosaurs founded by Leidy, Cope, and Marsh were based on material inadequate for the present standard of classification. The characters assigned to many species by these early investigators are now known to have only generic or family value. For this reason it seems inadvisable to append the long list of species of each formation.

Species known from the Belly River Beds on the Red Deer River

INVERTEBRATES

<i>Unio danæ</i> M. and H.	<i>Anadonta propatoris</i> White
<i>Unio</i> sp., cf. <i>U. supenawensis</i> Stanton	<i>Anadonta</i> ? sp.

PLANTS

<i>Cunninghammites elegans</i> ? (Corda)	<i>Castalia stantoni</i> Knowlton
Endlicher	<i>Castalia</i> nov. sp.
<i>Dammara</i> sp.	<i>Aspidium</i> sp.

VERTEBRATES

Pisces :

Myledaphus bipartitus Cope
Acipenser albertensis Lambe
Lepisosteus occidentalis Leidy
Rhineastes (Ceratodus) eruciferus
 Cope
Diphyodus longirostris Lambe

Batrachia :

Scapherpeton tectum Cope

Reptilia :

Plesiosauria
Cimoliasaurus magnus Leidy
 Chelonia
Aspideretes (Trionyx) foveatus
 Leidy
Basilemys (Adocus) variolosa
 Cope
Bæna antiqua Lambe
Boremys pulchra Lambe
Neurankylus eximius Lambe
 Lacertilia and Incertæ Sedis
Troödon formosus Leidy
Stegoceras validus Lambe

Crocodylia

Crocodylus humilis Leidy
Leidyosuchus canadensis Lambe

Megalosauria : Theropoda

Deinodon horridus Leidy
 ? " *explanatus* Cope
 ? " *hazenianus* Cope
Aublysodon mirandus Leidy

Stegosauria

Palæoscincus costatus Leidy
 ? *Ankylosaurus tutus* Lambe

Ornithomimida

Ornithomimus altus Lambe

Ceratopsia

Monoclonius (Centrosaurus) dawsoni Lambe
Brachyceratops montanensis Gilmore
Ceratops (Monoclonius) canadensis Lambe
Ceratops (Chasmosaurus) belli
Styracosaurus albertensis Lambe

Iguanodontia: Ornithopoda		Rhynchocephalia	
<i>Kritosaurus (Gryposaurus) notabilis</i> Lambe		<i>Champsosaurus profundus</i> Cope	
<i>Hypacrosaurus altispinus</i> Brown		“ <i>annectens</i>	
<i>Trachodon selwyni</i> Lambe		“ <i>brevicollis</i> Cope	
“ <i>marginatus</i> Lambe		Mammalia:	
“ <i>altidens</i> Lambe		<i>Ptilodus primævus</i> Lambe	
		<i>Boreodon matutinus</i> Lambe	

THE OJO ALAMO BEDS

This name was proposed by the writer (Bulletin of the American Museum of Natural History, volume XXVIII, article xxiv, pages 267-274, 1910) for the upper part of the Cretaceous series which unconformably underlies the Puerco formation at Ojo Alamo in New Mexico.

The Puerco is a clay formation, approximately 250 feet thick in the Ojo Alamo section, probably of fluvial origin. It contains an extensive and varied mammalian fauna of Paleocene age. The reptilian fauna, which is limited, embraces several genera and species of turtles, several undescribed species of crocodiles, three species of the Rhynchocephalian *Champsosaurus*, and a single species of the Ophidia. *Dinosaurs are notably absent.*

Invertebrates are not abundant and all are land and fresh water types. A small collection of plant remains has been identified by Doctor Knowlton, who states that “the age indicated is that of the Denver or perhaps as late as Fort Union.”

On Coal Creek, in the immediate vicinity of Ojo Alamo, the Puerco clays rest on massive sandstones which mark the top of a distinct series of sediments. At the point of contact Messrs. Granger and Sinclair have noted a distinct erosional unconformity, and 30 to 70 feet below this point another discordance appears where the sandstones rest on a thick bed of conglomerates. The underlying shales and sandstones, more than 200 feet thick, are lithologically distinct from the clays of the Puerco and the fauna is totally different.

No mammals have been recorded from this horizon, but reptilian remains, chiefly dinosaurs, are abundant.

Most of this material is poorly preserved and bones are rarely associated.

The Ceratopsian genera *Triceratops* and *Torosaurus*, which are characteristic of the Lance, do not occur in these beds, but the known fragmentary remains pertain to a more primitive smaller form comparable to *Monoclonius* or *Ceratops*.

The large carnivorous dinosaurs are smaller than *Tyrannosaurus* of the Lance and may be compared with *Albertosaurus* of the Edmonton or *Deinodon* of the Judith River.

The Trachodont dinosaurs furnish the most satisfactory evidence for the correlation of these beds. The genus *Trachodon*, which represents the family in the Lance formation, is not known here, but a primitive genus, *Kritosaurus*, of extraordinary skull development, described from this formation, is common.

Recently Mr. Lawrence M. Lambe, Ottawa Naturalist, volume xxxvii, number 11, February, 1914, described a perfect Trachodont skull from the Belly River beds of Canada. In all respects, including the remarkable development of the nasals, premaxillaries and prementary and the reduction of the orbital portion of the frontal, it agrees with the type of *Kritosaurus*, and there is no doubt of its generic identity.

A single species of turtle, *Thescelus rapiens* Hay, is not known elsewhere, though a closely related species, *T. insiliens*, is described from the base of the Lance.

Invertebrates are as yet unknown and the flora, represented by numerous fossil trees, has not been determined.

The vertebrate fauna is distinctly older than that of the Lance. I have expressed the opinion that it was comparable to the Edmonton, but from the recent discovery of *Kritosaurus* in the Belly River formation and the primitive structure of the contemporary dinosaurs the Ojo Alamo beds appear to be synchronous with the Judith (Belly River) formation.

The vertebrate fauna now known is as follows:

<i>Kritosaurus nayajovius</i> Brown	Crocodylia
? <i>Monoclonius</i> sp.	<i>Thescelus rapiens</i> Hay
? <i>Dienodon</i> sp.	<i>Lepisosteus</i> sp.

CONCLUSION

Briefly, in conclusion there is no doubt that the Hell Creek beds were synchronous with the "Lance," and little doubt that the Belly River and Ojo Alamo beds should be correlated with the Judith River. The Edmonton is intermediate in age between the Judith River and the Lance.

A comparison of the reptilian faunæ shows an uninterrupted succession of genera from the Judith River through to the close of the Lance. In some cases genera pass through without any marked change. They show those changes brought about through a lapse of time, but there is no evidence of any great migration changes which would be apparent as a result of any great diastrophic movement.

EVIDENCE OF THE PALEOCENE VERTEBRATE FAUNA ON
THE CRETACEOUS-TERTIARY PROBLEM¹

BY W. D. MATTHEW

(Presented before the Paleontological Society January 1, 1914)

CONTENTS

	Page
Use of the term Paleocene.....	381
Characters of the Paleocene vertebrate faunas.....	382
List of typical Paleocene vertebrate faunas.....	383
Comparison with Lance and Belly River faunas.....	386
Comparison with Wasatch (Lower Eocene) faunas.....	388
Characters of the Paskapoo fauna.....	388
Characters of Fort Union fauna, with list.....	389
Interpretation of the vertebrate faunas.....	390
Relations of the Judith River fauna.....	393
Correlation with the European succession.....	394
General discussion.....	394
Thanetian (Cernaysian) equivalent to Torrejon.....	395
List of Cernaysian fauna.....	395
Sparnacian and Ypresian equivalent to Wasatch.....	396
The Puerco has no certain equivalent in Europe.....	396
The Lance is equally difficult to correlate.....	396
Faunal migrations and diastrophism.....	397
Conclusions.....	399
Appendix A. Alleged occurrences of dinosaurs in Tertiary formations....	400
Appendix B. Unconformity between the Laramie and the Lance.....	401

USE OF THE TERM PALEOCENE

The character of the Paleocene fauna, its relations to the preceding and following faunæ, and its European correlations are an important part of the evidence on this problem.

¹ Manuscript received by the Secretary of the Geological Society June 14, 1914.

Contribution to the symposium held by the Paleontological Society at the Princeton meeting December 31, 1913, and January 1, 1914.

The term Paleocene, current in Europe,² has hardly come into use in this country. As applied here it denotes what we have been calling Basal Eocene, comprising the Fort Union, Puerco and Torrejon, and other equivalent formations older than the Wasatch or typical Lower Eocene. The reasons will appear later for its acceptance as an epoch distinct from the Eocene.

The typical and best known Paleocene fauna is that of the Puerco and Torrejon formations, Nacimiento terrane, of New Mexico. The stratigraphic relations of the faunæ of the four fossiliferous levels of this terrane have been explained by Doctor Sinclair. There is no marked stratigraphic break in the terrane, but there are two distinct faunæ, no species surviving from one to the other. Some of the genera and most of the families pass through, represented in the later horizon by distinct species or genera, usually more progressive. In their broader aspects the two faunæ have much in common to distinguish them from those of earlier or later age.

The Fort Union (not including the Lance) is provisionally correlated with the Nacimiento terrane. In its upper part is found a mammalian fauna composed in part of species identified with Torrejon species, but the rest of this fauna is not comparable with anything in either Puerco or Torrejon. A small flora from the Puerco is identified by Doctor Knowlton as indicating "Denver or perhaps as late as Fort Union" age. The diverse element of the Fort Union fauna is best interpreted as indicating a somewhat different environmental facies, somewhat more of a swampy delta and less of a floodplain type of deposit being indicated by the lithologic features.

CHARACTERS OF THE PALEOCENE VERTEBRATE FAUNAS

(1) The mammals are dominantly Placentals of archaic orders. A minority are Multituberculates, related (auct. Broom)³ to the existing Monotremes. Approximately 10 per cent of the fauna is Multituberculate. The remainder belong to groups of placentals which became extinct during the Eocene. The later Tertiary and modern orders of mammals are not present except the Carnivora and certain groups doubtfully referred to Insectivora and Edentates. There are no Perissodactyls, Artiodactyls, Rodents, or Primates, these orders appearing suddenly at the beginning of the true Eocene.

² But not always with the significance here given to it. Some authors include in it the London Clay, equivalent to our Wasatch or Lower Eocene.

³ I do not indorse this view. New evidence bearing on it will shortly be published by Mr. Granger.

(2) The Multituberculates are nearly related to those of the Lance formation, but the species of each phylum are larger and more specialized. The placentals have apparently no predecessors in the Lance; at least this is true, in my judgment, of the bulk of the placental fauna and so far as the present evidence indicates. The Lance mammal fauna is so fragmentary that statements about its composition should be carefully qualified.

(3) The reptiles are chiefly Chelonia, Crocodilia, and Choristodera. One snake has been recorded; lizards were present, although not recorded. No dinosaurs are present;⁴ the marine reptiles of the Mesozoic would not be expected. The reptiles all belong to families that originated in the Cretaceous (Belly River) or earlier. Three of the families still survive, one disappeared with the Eocene, another with the Paleocene. The dominant Tertiary families of Chelonians (Emydidae and Testudinidae) are not present, appearing first in the Lower Eocene. The absence of Tertiary types of lizards and snakes is of little weight, as it may be merely a matter of defective record.

LIST OF TYPICAL PALEOCENE VERTEBRATE FAUNAS

	Puerco.	Torreon.	Clark Fork.
REPTILIA			
Order Testudines			
Fam. Baenidae (Cretaceous-Eocene)			
<i>Baena escavada</i> Hay.....		×	
Fam. Dermatemyidae (Cretaceous-Recent)			
<i>Hoplochelys crassa</i> Hay.....	×		
" <i>salicns</i> Hay.....		×	
" <i>paludosa</i> Hay.....		×	
<i>Alamosemys substriata</i> Hay.....		×	
Fam. Trionychidae (Cretaceous-Recent)			
<i>Conchochelys admirabilis</i> Hay.....	×		
<i>Aspideretes sagatus</i> Hay.....	×		
" <i>puercensis</i> Hay.....	×		
" <i>singularis</i> Hay.....		×	
Order Choristodera			
Fam. Champsoosauridae (Cretaceous-Paleocene)			
<i>Champsosaurus australis</i> Cope.....		×	
" <i>saponensis</i> Cope.....		×	
Order Serpentes			
Fam. ?? Crotalidae (?? Cretaceous-Recent)			
<i>Helagras prisciformis</i> Cope ⁵		×	
Order Crocodilia			
Fam. Crocodylidae (Cretaceous-Recent)			
<i>Crocodylus stavelianus</i> Cope ⁶		×	

⁴ But see appendix, p. 400.

⁵ Generic and family reference needs revision.

⁶ The generic position of these Eocene and Paleocene crocodiles is wholly doubtful.

	Pueroo.	Torrejon.	Clark Fork.
MAMMALIA			
Order Multituberculata (Triassic-Paleocene)			
Fam. Plagiaulacidae			
<i>"Neoplagiular"</i> <i>americanus</i> Cope.....	×		
" <i>molestus</i> Cope.....		×	
" sp.			*
<i>Ptilodus medievus</i> Cope.....		×	
" <i>trovessartianus</i> Cope.....		×	
<i>Polymastodon taensis</i> Cope.....	×		
" <i>attenuatus</i> Cope.....	×		
" <i>fissidens</i> Cope.....		?	
<i>Catopsalis foliatus</i> Cope.....	×		
Order Feræ (sub-ord. Creodonta)			
Fam. Miacidæ (Paleocene-Eocene)			
<i>Didymictis haydenianus</i> Cope.....		×	
" <i>cf. leptomytus</i> Cope.....			×
Fam. Arctocyonidæ (Paleocene-Lower Eocene)			
<i>Clanodon corrugatus</i>		×	
" <i>ferox</i>		×	
? " <i>protogonioides</i>	?	×	
Fam. Mesonychidæ (Paleocene-Eocene)			
<i>Triisodon quivirensis</i> Cope.....	×		
" <i>heilprinianus</i> Cope.....	×		
" <i>gaurdianus</i> Cope.....	×		
<i>Sarcothraustes antiquus</i> Cope.....		×	
<i>Goniacodon levisanus</i> Cope.....		×	
<i>Microclenodon assurgens</i> Cope.....		×	
<i>Dissacus saurognathus</i> Wortman.....		×	
" <i>navajovius</i> Cope.....		×	
Fam. Oxyclenidæ (Paleocene) [†]			
<i>Oxyclenus cuspidatus</i> Cope.....	×		
" <i>simplex</i> Cope.....	×		
<i>Loxolophus hyattianus</i> Cope.....	×		
" <i>priscus</i> Cope.....	×		
" <i>attenuatus</i> O. & E.	×		
<i>Carcinodon filholianus</i> Cope.....	×		
<i>Paradoxodon rutimeyeranus</i> Cope.....	×		
<i>Protogonodon pentacus</i>	×		
<i>Chriacus pelvidens</i>		×	
" <i>truncatus</i>		×	
" <i>baldwini</i>		×	
" <i>schlosserianus</i>		×	
<i>Tricentes subtrigonus</i>		×	
" <i>crassicollidens</i>		×	
<i>Deltatherium fundaminis</i>		×	
Fam. Oxyænidae (Upper Paleocene-Eocene)			
<i>Dipsalidictis platypus</i> indesc.....			×
<i>Palæonictis</i> or <i>Oxyæna</i> , sp. indesc.....			×
<i>Oxyæna æquidens</i> sp. indesc.....			×
Order Insectivora (Paleocene-Recent)			
Fam.? Centetidæ (? Paleocene-Recent)			
<i>Palæoryctes puercensis</i> Matthew.....		×	
Fam.? Pantolestidæ (? Paleocene-Eocene)			
<i>Pentacodon inversus</i> Cope.....		×	

* Sand Coulee beds, at base of true Eocene.

† One doubtful species of *Chriacus* in the Lower Eocene.

	Puerco.	Torrejon.	Clark Fork.
Fam. Mixodectidæ (Paleocene-? Eocene)			
<i>Mixodectes pungens</i>		×	
“ <i>crassiusculus</i>		×	
<i>Indrodon malaris</i>		×	
Order Tæniodonta (?? = Xenarthra)			
Fam. Stylinodontidæ (Paleocene-Eocene)			
<i>Wortmania otariidens</i> Cope.....	×		
<i>Psittacotherium multifragum</i> Cope.....		×	
Fam. Conoryctidæ (Paleocene)			
<i>Onychodectes tisonensis</i> Cope.....	×		
“ <i>rarus</i> O. & E.....	×		
<i>Conoryctes comma</i> Cope.....		×	
Order Xenarthra (Palaenodonta, Paleocene-Eocene)			
Fam. Metacheiromyidæ			
<i>Palaenodon</i> sp. indesc.....			×
Order Condylarthra			
Fam. Phenacodontidæ (Paleocene-L'r Eocene)			
<i>Tetraclenodon puercensis</i> Cope.....		×	
“ <i>minor</i> Matthew.....		×	
<i>Phenacodus</i> sp. div.....			×
Fam. Mioclænidæ (Paleocene)			
<i>Mioclænus turgidus</i>		×	
“ <i>lydekkerianus</i>		×	
“ <i>lemuroides</i>		×	
“ <i>acolytus</i>		×	
“ <i>turgidunculus</i>	×		
“ <i>inæquidens</i>		×	
<i>Protoselenæ opisthacus</i>		×	
<i>Oxyacodon</i> ^s <i>apiculatus</i> O. & E.....		×	
“ <i>agapetillus</i> Cope.....	×		
Order Taligradæ			
Fam. Periptychidæ (Paleocene)			
<i>Periptychus carinidens</i> Cope.....		×	
“ <i>rhabdodon</i> Cope.....		×	
“ <i>coarctatus</i> Cope.....	×		
<i>Ectoconus ditrigonus</i> Cope.....	×		
<i>Conacodon entoconus</i> Cope.....	×		
“ <i>cophater</i> Cope.....	×		
<i>Hemithlæus kowalevskianus</i> Cope.....	×		
<i>Anisonchus gillianus</i> Cope.....	×		
“ <i>sectorius</i> Cope.....		×	
<i>Haploconus lineatus</i> Cope.....		×	
“ <i>corniculatus</i> Cope.....		×	
Fam. Pantolambdæ (Paleocene)			
<i>Pantolambda bathnodon</i>		×	
“ <i>cavirictus</i>		×	
Order Amblypoda			
Fam. Bathyopsidæ (Up. Paleocene-L'r Eocene)			
Gen. indesc.....			×

^s May be better placed under Periptychidæ.

COMPARISON WITH LANCE AND BELLY RIVER FAUNAS

(1) The vertebrates of the Lance and Belly River are: (1) Horned Dinosaurs (Ceratopsia), (2) Duck-billed Dinosaurs (Trachodonts), (3) Large carnivorous Dinosaurs (Megalosaurs), (4) Armored Dinosaurs (Ankylosaurs), (5) Smaller Dinosaurs of the predentate and theropod divisions, not yet cleared up as to relationship, (6) Chelonians of the families Baenidæ, Dermatemydidæ, and Trionychidæ, (7) Crocodiles of the family Crocodilidæ, (8) Choristodera (fam. Champsosauridæ), (9) Lizards of the family? Iguanidæ (recorded from Lance only), (10) Multituberculate mammals, (11) Trituberculate mammals (positively recorded from Lance only), some demonstrably marsupials, others of uncertain relationship, none demonstrably Placentals.

Comparing the Belly River with the Lance, we find the same groups represented throughout, exceptions in (9) and (11) being probably a matter of imperfect record, as these groups are extremely rare. Among the Dinosaurs the Belly River types appear to be more varied and less extremely specialized, the phyla which pass through being represented by more primitive stages in the Belly River. Among the mammals the multituberculate mammals are recorded in the Belly River by a single genus, apparently a more primitive stage of one of the Lance phyla. Additional specimens will be diligently searched for. The trituberculate mammals have not yet been found in the Belly River, except for a single tooth of uncertain affinities, and are rare in the Lance.⁹ Whatever their affinities, these mammals do not appear to include ancestral stages of the placental phyla of the Paleocene, certainly not of the majority, probably not of any of them. The chelonia, crocodilia, and choristodera belong to the same phyla, in large part to the same genera, in the Belly River as in the Lance, and afford little evidence of progressive evolution.

Comparing the Lance with the Paleocene, we find that none of the numerous Dinosaur phyla pass through. The entire order becomes extinct and none have been found associated with the placental mammal fauna of the Paleocene (but see Appendix A).⁷ The Chelonians, Crocodiles, and Choristodera pass through, represented by the same phyla and without much progressive evolution as far as known. The Multituberculata pass through, but with an appreciable amount of progressive evolution, amounting in one phylum to generic, in another to marked specific difference. The Trituberculate mammals apparently disappear, al-

⁹ It is worthy of note that the greater abundance of small mammals in the Lance as compared with the Belly River is wholly due to the presence of numerous ant-hills scattered over the exposures. Practically all the Lance mammals have been found in these ant-hills.

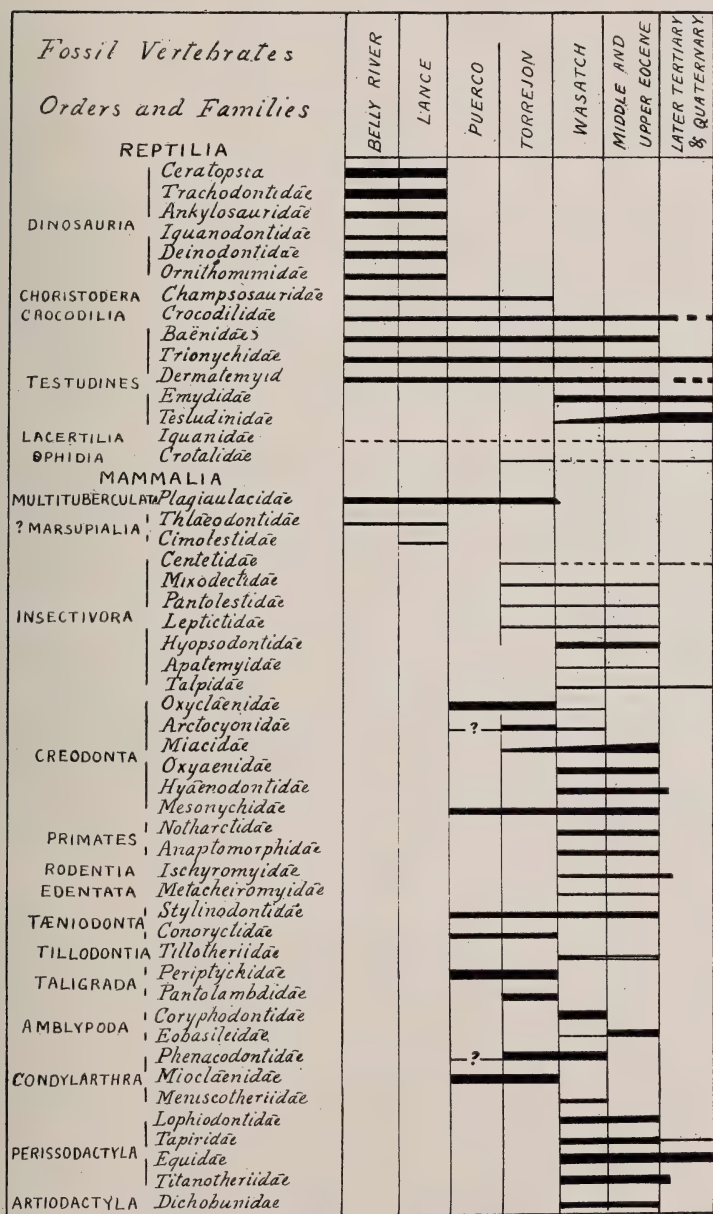


FIGURE 1.—Geologic Range of Land Vertebrates in typical American continental Formations of late Cretaceous and Tertiary Time

though some of them may have left descendants in the rare and little known marsupials and small insectivores of our Tertiary formations. The numerous phyla of placental mammals which take the place of the dinosaurs and mammals of the Lance are not derivatives of any part of the Lance fauna, but a new appearance.

COMPARISON WITH WASATCH (LOWER EOCENE) FAUNAS

(1) The Multituberculates disappear at the end of the Paleocene, although a few rare survivors (three specimens) have been found at the very base of the Wasatch.

(2) Some of the placental phyla disappear at the end of the Paleocene, but over half of the families survive into the Wasatch, some into the Middle or Upper Eocene (see U. S. Geological Survey Bulletin Number 361, pages 100-103).

(3) The larger part of the Eocene fauna from the base of the Wasatch up is composed of genera of Perissodactyla, Artiodactyla, Rodents, and Primates; orders not found in the Paleocene. They are not descended from known Paleocene ancestors, but represent a newly arriving fauna. In the Clark Fork beds at the top of the Paleocene we find these orders still absent, although the genera of the Paleocene orders are identical with those of the Wasatch and more advanced than those of the Torrejon.

(4) The Choristodera disappear. The crocodiles and the families Baenidae, Dermatemydidæ, and Trionychidae among chelonians continue through with little change. The dominant groups of Tertiary chelonians, Emydidae and Testudinidae, first appear in the Wasatch (but not at first in great numbers) and are not derivable from known Paleocene chelonians.

CHARACTERS OF THE PASKAPOO FAUNA

A small fauna has been secured by Mr. Barnum Brown from the Paskapoo beds in Alberta. It consists wholly of mammals, no dinosaurs occurring in this formation. The mammals, according to Mr. Brown's identifications, checked by the present writer, are unmistakably those of the Lance fauna in part, but include an element which has not been found in the Lance and appears to belong to the Paleocene groups of mammals, although none of its representatives compare at all closely with any Puerco or Torrejon genera. I suspect that it will be found to compare more nearly with the Fort Union fauna. It is evident at all events that there was a considerable element of placental mammals in the fauna. But the Multituberculates are those of the Lance and some of the trituberculates appear to be identical. There is no indication of the presence of any of the Eocene orders of placentals.

List of Paskapoo Mammalia

Multituberculata :

Meniscæssus sp. indesc.*Ptilodus* sp.*Cimolodon* sp.

Trituberculata :

Didelphops sp.? *Batodon* sp.? *Thlæodon* sp.

? Gen. indesc.

? Gen. indesc.

? Pantolestidæ gen. indet.

? Creodonta and Condylarthra

?? Taligrada

} ? Marsupialia

} ? Insectivora

CHARACTERS OF THE FORT UNION FAUNA, WITH LIST

This fauna as described by Douglass and Gidley consists of a few mammals, and Hay has described a single *Trionychid* chelonian. A considerable collection of mammals from the upper Fort Union will shortly be described by Mr. Gidley; other reptilia are probably present, but have not been described.

The mammalian fauna corresponds in part to that of the Torrejon. It includes a minor element of Multituberculates, of which *Ptilodus* is the only described genus, the species closely allied to those of the Torrejon. A number of Placental genera of the Torrejon are represented, but there are several genera, apparently Placentals, which have no near relatives in the typical Paleocene faunæ.

In the following list the mammals are auct. Douglass 1908, but I have added some critical comments based on his figures and descriptions.

List of Fort Union Vertebrates

REPTILIA

Order Testudines

Fam. Trionychidæ

Aspideretes nassau

MAMMALIA

Order Multituberculata

Fam. Plagiaulacidæ

Ptilodus montanus (Torrejon stage of evolution)

Order ? Marsupialia

Fam. ? Cimolestidæ Marsh

? *Batodon* sp. (Not figured; valueless in correlation)? *Cimolestes* sp. (Reference very questionable; ?placental)

Fam. Didelphyidæ

? *Peratherium* sp.

- Fam. ? Epanorthidæ
 - Picrodus silberlingi*. (Family position doubtful, as this family is unknown outside of South America. Possibly a Multituberculata of undescribed family)
- Order Insectivora
 - Fam. incert.
 - Coriphagus montanus*
 - Megapterna minuta*
 - Fam. ? Mixodectidæ
 - ? *Mixodectes* sp. (Not Mixodectidæ; doubtfully Insectivore)
- Order Carnivora (Feræ)
 - Fam. Oxyclænidæ
 - Protochriacus* sp. (Reference questionable)
 - ? *Chriacus* sp. (Not figured; of no value in correlation)
 - ? *Tricentes* sp.
 - ? *Deltatherium*
- Order Tæniodonta
 - Fam. Stylinodontidæ
 - Calamodon* sp. (Agrees better with Psittacotherium)
- Order Condylarthra
 - Fam. Phenacodontidæ
 - Euprotogonia* (= Tetracænodon) sp.
 - Fam. Mioclænidæ
 - Mioclænus* sp.
- Order Taligrada
 - Fam. Pantolambdidæ
 - Pantolambda* sp.
 - Fam. Periptychidæ
 - Anisonchus* sp.

INTERPRETATION OF THE VERTEBRATE FAUNAS

The evidence of fossil vertebrates in correlation is very valuable, provided it is interpreted correctly. Owing to the complex structure of the hard parts preserved and their capacity for relatively rapid and extreme progressive and adaptive changes in these hard parts, they afford a more precise and exact measure of time than do any other animals. This is peculiarly true of the mammals; dinosaurs, perhaps, rank next; other vertebrates are much less progressive. But as they respond more quickly to the opportunities for evolution afforded by lapse of time, so also they are more sensitive to difference of environment and more subject to change of geographic range and great migration movements, conditioned by great environmental changes in other regions. Moreover, the evidence is often fragmentary, and the reference of recorded genera and species doubtful and provisional to a varying degree. Omitting this element of doubt, the difference between two vertebrate faunæ may be due to

1. Lapse of time.
2. Difference of local environment.
3. Migration movements representing a change in environment somewhere else, not necessarily in the region concerned.

Lapse of time will be represented by changes in the evolutionary stages of the phyla which pass through from one to the other. It will not bring about sudden changes in the composition of the fauna, although certain phyla may diminish, while others increase in numbers.

A difference of local environment will involve the absence of certain groups of more or less restricted habitat, whose continued existence may yet be known by their presence in both earlier and later faunæ of different facies, or may be inferred from more indirect evidence.

A migration movement may cause the sudden appearance of new groups, the disappearance or extinction of older ones, with or without any apparent change in the facies or environmental type of the faunæ compared.

In attempting to apply the vertebrate evidence to correlation of the later Cretaceous and earlier Tertiary formations, these principles must be kept in mind or the results will be misleading. If properly understood they serve to reconcile what have appeared to some authors to be contradictory statements by vertebrate paleontologists. Marsh in his description of the Lance fauna lays weight on its resemblance to the Jurassic and Lower Comanchic faunæ. This is quite correct, inasmuch as it consists of Multituberculates unknown in the Tertiary except for a few Paleocene survivors, and of Trituberculates of rather remote affinity to the Tertiary placentals and similar in several features to those of the Jurassic. Osborn, on the other hand, pointed out that the Multituberculates of the Lance were much more closely allied to their Paleocene successors than to their Jurassic ancestors, and rightly concluded that there was no wide time-gap between the Lance and the Paleocene. The evidence as presented by Marsh and Osborn is not conflicting, but it presents different aspects of relationship. The Lance mammal fauna is near to that of the Jurassic in facies; it is much nearer in time to the Paleocene faunæ.

Comparing the Belly River and Lance faunæ, we find evidence of a considerable gap in time as represented especially by the progressive evolution in the Ceratopsia and other dinosaurs. But there is no good evidence of any change in facies or of the appearance of new immigrant groups of reptilia or mammalia. The reptilian phyla one and all continue through, some with little change, others with more considerable progressive evolution. The scanty evidences of mammals from the Belly

River indicate a fauna of the same facies as the Lance, doubtfully more primitive in stage.

Comparing the Lance with the Puerco and Torrejon, we find a fauna of very different facies, but indicating no very wide gap in time. It is not very clear whether the great faunal difference is due to diverse local environments or to a great movement of faunal migration, but a combination of both seems to fit the data most exactly.

Comparing the Puerco and Torrejon with the Wasatch, we find faunae which appear to represent similar facies, but a very marked change in the sudden appearance of new orders and families of mammals and reptiles which can best be accounted for as immigrants. The lapse of time, as measured by the change in phyla which pass through, is not very great between Torrejon and Wasatch and very slight between Clark Fork beds and Wasatch. But the close of the Paleocene is marked by a great migration movement.

Comparing the mammal fauna of the Upper Fort Union with that of the Torrejon, we find that it appears to be of the same age, as indicated by the identity of a part of the fauna. But it apparently represents a somewhat different facies, with certain points of analogy to the Lance.

Comparing the Paskapoo fauna with the Lance, it appears by the same criteria to be equivalent or only slightly later in age, while apparently older than the Puerco and presumptively older than the Upper Fort Union; but it represents a facies very different from that of the Lance, corresponding more nearly with that of the Puerco and Torrejon, and perhaps still more closely with that of the Fort Union. It throws some light on the interpretation of the break between Lance and Puerco, for it contains an element that may be regarded as ancestral to a part of the Paleocene placentals, but does not appear to be related to the major and more progressive part of them. This would indicate that the absence from the Lance of the more primitive and archaic groups of the Puerco-Torrejon fauna is a matter of facies; but that the absence of the larger, more progressive and abundant Paleocene placentals from the Lance is to be ascribed to a migration movement at its close. The evidence on this point is, however, too scanty to be of any considerable weight.

By similar methods of correlation Brown has shown that the Edmonton formation underlying the Paskapoo and overlying the Pierre and the Ojo Alamo beds, which lie unconformably beneath the Puerco, are older than the Lance and equivalent to the Belly River, and that the Hell Creek beds of Montana are equivalent in age to the typical Lance, all representing nearly the same facies, but the Canadian formations somewhat more accessible to the marine fauna, as indicated by the finding of

a Plesiosaur skeleton in the Edmonton, and by the characters of the invertebrate fauna.

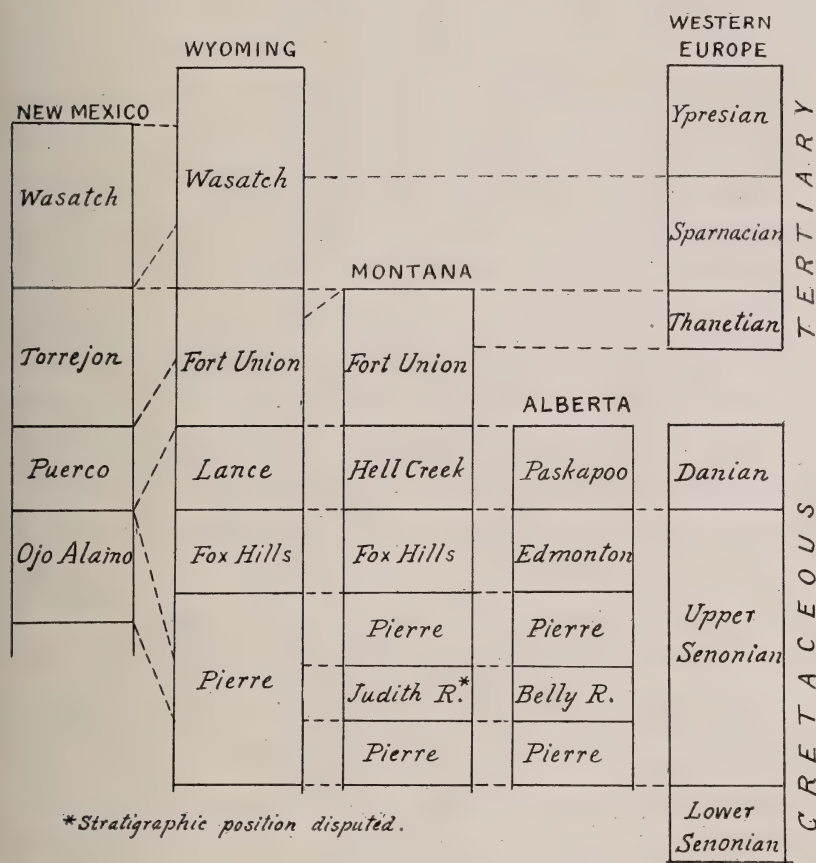


FIGURE 2.—Approximate Correlations of typical Formations of the late Cretaceous and early Tertiary in Europe and western America based on their Vertebrate Faunas

RELATIONS OF THE JUDITH RIVER FAUNA

On account of the disputed age of this formation it is better to rest the vertebrate evidence on other faunæ of unquestionable stratigraphic relations. I may say, however, that the fauna described by Cope from beds which Peale regards as equivalent to the Lance is unquestionably closely allied to that of the Belly River and of approximately the same age. The attempt made by Peale to show that it is identical with that of the Lance is based chiefly on a list of fragmentary specimens which, as stated by Hatcher (*American Geologist*, 1903, page 374) are practi-

cally valueless for exact correlation. His attempt to show that there are any common genera among the *Ceratopsia* hinges entirely on the identification of a specimen from the Denver beds, identified by Marsh as *Ceratops montanus* or some nearly allied reptile,¹⁰ and stated by Lull¹¹ to be "too fragmentary for accurate determination."

It will be sufficient to say that the published lists of species identified from both Judith River and Lance are in large part based on material too fragmentary for exact identification and of no value in exact correlation, as has been shown in detail by Mr. Hatcher, and that all that are sufficiently characteristic and complete to be of use in this way show that the "Judith River" of Cope's localities is of practically the same age and facies as the Belly River.¹²

The age of the Judith River, like any other problem in correlation, must be settled by bringing *all* the evidence into conformity. It can not be settled by balancing conflicting evidence and assigning more weight to one than to another class of data. Doctor Peale's attempt to bring all the evidence into conformity is undoubtedly right in principle, although biassed in method. But his solution of the vertebrate evidence is impossible of acceptance, especially in view of the recent researches in the Belly River fauna.

CORRELATION WITH THE EUROPEAN SUCCESSION

GENERAL DISCUSSION

The dividing line between Cretaceous and Tertiary in England is drawn between the uppermost beds of the chalk and the littoral and "fresh-water" beds which overlie it—the Thanet sands and London clay. But between these there is known to be a very considerable gap in time. This gap is partly filled on the continent by various intermediate formations, the highest stage of the chalk, the Danian, being absent in the English succession. While this is generally recognized as Cretaceous, there appears to be a difference of opinion as to the position of the Montien of Belgium and its equivalents. De Lapparent and other writers reckon it as the latest stage of the Cretaceous, while Dollo, Rutot, and

¹⁰ Amer. Jour. Sci., vol. xxxvi, 1888, p. 477.

¹¹ *Ceratopsia* monograph, p. 183. As Doctor Peale quotes and comments on the next preceding sentence in this reference, he could hardly have missed seeing this statement, to which he makes no allusion, although it invalidates his whole argument on this point.

¹² A recent note in "Science" by Mr. C. H. Sternberg puts a new light on the evidence. If his recollection of the stratigraphy is correct, Cope's *Ceratopsia* specimens came from a formation underlying the Pierre, while most of his fragmentary material came from the typical localities which Mr. Sternberg recalls as overlying the Pierre. The evidence from fossil vertebrates would accord with this, although I do not think it in any way confirms it.

others consider it as the earliest Tertiary, equivalent in age to the Thanet sands. Here, as in our own succession, the difficulty lies in the correlation of faunas of diverse facies. Into the place of these disputed formations it will not be necessary to go. It is sufficient to state that the latest unquestioned Cretaceous stage is the Danian and the earliest unquestioned Tertiary stage the Thanetian.

THANETIAN (CERNAYSIAN), EQUIVALENT TO TORREJON

The Cernay conglomerates, Rilly sands, and the La Fère glauconites have furnished a small fauna of mammals and reptiles, comparable in facies to our Torrejon and apparently of equal age. *Arctocyon*, *Dissacus*, and *Neoplagiaulax* are very characteristic types closely allied or identical with Torrejon genera. The remainder of the fauna affords rather indecisive comparison with the Torrejon except for *Pleuraspidotherium*, which¹³ is singularly like certain isolated teeth from the Paskapoo. A thorough revision of this Cernaysian fauna is very much needed, but there appears to be little present prospect of it.

Whether the Cernaysian fauna corresponds with the whole of the Thanetian or only a part of it is impossible to say.

LIST OF CERNAYSIAN FAUNA

Creodonta :

<i>Arctocyon primævus</i>	}	Close to <i>Clanodon</i> sp. div.
" <i>gervaisii</i>		
" <i>duelli</i>		
<i>Hyænodictis gaudryi</i>	}	= <i>Dissacus</i>
<i>Dissacus europæus</i>		

Insectivora :

<i>Tricuspidon</i>	}	Possibly related to <i>Palæoryctes</i>
<i>Procynictis</i>		
<i>Orthaspidotherium</i>		
<i>Pleuraspidotherium aumonieri</i>	}	Cf. ? Paskapoo fauna
" <i>delessei</i>		
<i>Plesiadapis tricuspidentis</i>	}	Possibly comparable with the small species of <i>Miocænus</i>
" <i>remensis</i>		
" <i>gervaisii</i>		
<i>Adapisorex gaudryi</i>	}	
" <i>chevilloni</i>		
<i>Adapisoriculus minimus</i>		
<i>Protoadapis copei</i>		A doubtful primate

Multituberculata :

<i>Neoplagiaulax cocænus</i>	}	Close to <i>Ptilodus</i> sp. div.
" <i>marshii</i>		
" <i>copei</i>		

¹³ Auct. Osborn's figures in his review of the Cernaysian mammalia.

SPARNACIAN AND YPRESIAN EQUIVALENT TO WASATCH

The London Clay, Argiles plastiques of the Paris basin, and equivalent formations in Belgium and elsewhere contain the *Coryphodon* fauna, which extends through our Lower Eocene or Wasatch faunæ. The older part (Sparnacian) is probably equivalent to the Gray Bull or Systemodon Zone of the Wasatch, marked by the sudden appearance of *Coryphodon*, *Palæonictis*, *Eohippus*, *Pachyena*. The newer part (Ypresian) may be more doubtfully compared with the upper part of our Wasatch, the Lysite and Lost Cabin (Heptodon and Lambdotherium zones), the evolution of the faunæ being on divergent lines, with no new invading migrants to link them together.

THE PUERCO HAS NO CERTAIN EQUIVALENT IN EUROPE

It is arbitrarily correlated by Osborn with the Montian. But the only mammal found in the Montian is *Coryphodon* from the upper beds of that horizon, and this, if correctly identified, would indicate not Paleocene, but Eocene age of a part of the formation. On the other hand, in the Lower Landenian of later age, according to Dollo, the only recorded vertebrate of any value in exact correlation is *Champsosaurus*, a characteristic Cretaceous-Paleocene genus. Dollo, however, correlates the horizon as Lower Eocene. In view of these contradictory data, and of the doubtful character of such slight evidence and the frequent confusion due to redeposit in these scattered littoral formations, it seems better to leave the Montian problem for our European confrères to solve and content ourselves with the reasonably certain data.

THE LANCE IS EQUALLY DIFFICULT TO CORRELATE

There are no European formations of corresponding facies in the late Cretaceous. Dinosaurs are found in the later Cretacic of Europe at least as late as the Mæstrichtian (= Upper Senonian or Danian), but not sufficiently abundant or complete to afford correlation data. The Gosau formation is of similar facies to the Lance, but is much older—Lower Senonian. No dinosaurs are found in the Montian or any of the European formations that are reckoned to the Tertiary. The Lance flora is shown by Knowlton to be nearly allied to the Fort Union flora, and through this to the Paleocene floras of Gelinden and Sezannes. But, as there are no late Cretacic floras of similar type to compare it with, it is *not* thereby shown to be post-Cretacic, as Stanton has observed.

FAUNAL MIGRATIONS AND DIASTROPHISM

In the foregoing discussion of the vertebrate faunas of the late Cretacic and early Tertiary the differences in faunæ have been ascribed to three factors: (1) Lapse of time; (2) Difference of facies; (3) Wide-spread migration movements. The first affords a measure of the time interval between two formations. The second, when occurring in superposed formations, indicates a change in local conditions, often accompanied by a stratigraphic break or unconformity. The third, occurring often independently of any local changes in environment, points to changes in the conditions in some other region, usually in the center of dispersal, where the migration movements originated.

It is usually assumed by paleogeographers that these changes consisted in the union of regions formerly isolated, permitting land animals to invade areas hitherto isolated. But it has been very conclusively shown by C. Hart Merriam that the range of land mammals is limited not so much by mountain barriers or even oceanic barriers as it is by climatic zones. This is also true of land reptiles, and presumably of the land fauna generally. A change in range is therefore conditioned not merely by the land connection which permits or facilitates the migration, but by climatic change which forces the movement through the changed environment. This climatic change will be largely dependent on great and wide-spread movements of elevation or submergence. A wide-ranging migration movement resulting in the simultaneous appearance in Europe and North America of identical new types is, therefore, to be ascribed not merely to such slight changes as might serve to make a land connection, but to a great movement of upheaval of the land, affecting a large part, if not the whole, of the intervening region from which the new types are presumably derived.

These great migration movements therefore I regard as caused by diastrophism. If the evidence is properly interpreted and the migrations adequately proved, they afford, it seems to me, the most reliable and in some sense the only evidence of diastrophism; for it is not possible, save through the evidence of the paleontologic record, to prove that the movements of which the stratigraphy gives evidence were simultaneous or to correlate them exactly in different regions. The extent and amount of the stratigraphic break between the Lance and the formations of the Montana group is a matter of dispute. But were it not, I fail to see how we could correlate it with the break between the European Cretacic and Tertiary series save through the faunal evidence.

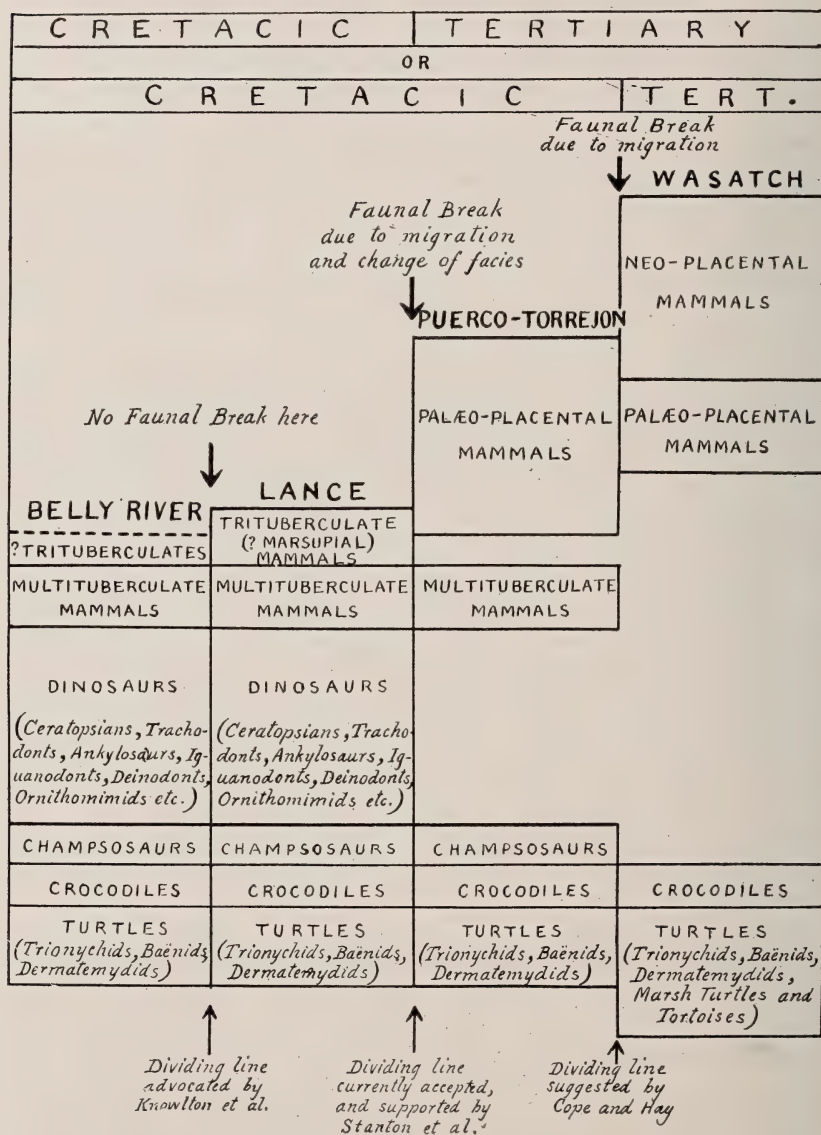


FIGURE 3.—Division between Cretaceous and Tertiary Periods, as indicated by terrestrial Vertebrate Fauna of typical western Formations

As I read the evidence from the vertebrates it is to this effect:

(1) From the Belly River to the Lance there is a considerable lapse in time, but they represent the same faunal facies and they indicate that there was no great migration movement intervening, and hence *no great upheaval*, either continental or universal. There was undoubtedly a considerable local uplift along the Rocky Mountain ridges and extensive recession of the sea from the plains to eastward of them.

(2) Between the Lance and the Paleocene there is a somewhat smaller lapse in time, but a very marked change in fauna; but they do not represent the same facies, and while a great migration movement is probably indicated by the extinction of the Dinosaur phyla and incoming of certain groups of placental mammals (Creodonta, Condylarthra, etcetera) its extent remains a little uncertain.

(3) Between the Paleocene and Eocene a great migration movement intervenes, the progressive orders of placental mammals, of turtles, and perhaps other groups appearing simultaneously in Europe and North America. The lapse of time between the uppermost Paleocene and lowest Eocene is slight.

If, therefore, we are to use diastrophic criteria as the basis of our geologic classification, the dividing line between Cretaceous and Tertiary should be drawn either between the Lance and the Paleocene or between the Paleocene and Eocene. It should *not* be drawn between Belly River and Lance.

It is perhaps apropos to recall that the late Professor Cope was for a long time of the opinion that the Paleocene should not be included in the Tertiary, but distinguished along with the Lance and associated faunæ as post-Cretaceous. Doctor Hay has also expressed the opinion that it might be better to include the Puerco and perhaps also the Torrejon in the Cretaceous.

CONCLUSIONS

The question to my mind shapes itself thus: Does the evidence conclusively support the present classification; and, if not, is it sufficiently conclusive to warrant our changing it? I have indicated what I regard as the weight and trend of the vertebrate evidence. Without entering into any detailed criticism of the stratigraphic and paleobotanic evidence, a task for which others are far more competent, I may say that to me it appears to be inconclusive because it does not allow for the characteristics of epicontinental formations nor for the varying facies of faunas and

floras; that the asserted magnitude of the break between Laramie and Lance rests not on evidence, but on a definition of the Laramie (see Appendix B), and that no really adequate evidence has been adduced of its relations to the Cretacic-Tertiary break in Europe. The paleobotanic argument for placing the Lance in the Tertiary is the resemblance of its flora to that of the Paleocene and its great difference from that of the true Laramie. But there is no evidence that the Lance flora was absent from Europe in the late Cretaceous, and the Laramie clearly represents a different facies from the Lance. Doctor Knowlton has insisted strongly on the entire absence of dinosaurs in the true Laramie, apparently with the idea that it showed it to be much older than the Lance. But as the same phyla of dinosaurs are present in the older Belly River and in the newer Lance, their absence from the Laramie is obviously due to a difference in environmental conditions. The facies of the fauna is different and much, if not all, of the difference in flora should be ascribed to this cause.

For these and many other reasons, the evidence summarized by Doctor Knowlton in favor of transferring the Lance and associated formations to the Tertiary appears to me inconclusive, and it is directly in conflict with the evidence from fossil vertebrates, so far as I am able to understand it. But in view of this conflict, real or apparent, I do not regard the problem as a settled one. Until all the data have been brought into conformity and the exact position of the principal diastrophic break conclusively shown from more convincing data than are at present available, it seems to me better to hold to the current classification, which is at least supported by evidence better, in my opinion, than any that has been brought forward in favor of Doctor Knowlton's views.

APPENDIX A. ALLEGED OCCURRENCES OF DINOSAURS IN TERTIARY FORMATIONS

Doctor Knowlton has asserted that dinosaurs do occur in the Fort Union formation. The evidence, as far as I am acquainted with it, is that dinosaur remains have been found some hundreds of feet above an arbitrary line taken as the line of separation between Lance and Fort Union. They have not been found associated with Paleocene vertebrates; nor are they known to be different from the dinosaurs of the Lance beds beneath them. Fossil plants if found associated would give no trustworthy evidence, since the floras of the Lance and Fort Union are almost identical, most of the species being common to the two. The obvious inference would be that the dividing line, confessedly arbitrary, was

drawn in the wrong place. A precisely parallel case is shown by Sinclair in his contribution on the Puerco-Torrejon stratigraphy. The division between these two formations was arbitrarily placed by Gardner at a certain sandstone level between the upper and lower fossiliferous beds, the upper carrying the Torrejon fauna, the lower the Puerco fauna. Subsequently Granger and Sinclair found the Torrejon fauna at a level 100 feet below Gardner's line of division. The natural conclusion was that the division line had been placed at least 100 feet too high up.

As to the alleged occurrences of Dinosaurs associated with Tertiary mammals in Patagonia, this is positively asserted by Ameghino and Roth, who, however, consider the beds Cretaceous, not Tertiary. Loomis, who has recently collected in these formations, has shown that the mammal-bearing beds occur in stream-channels and pockets in the older formations, and believes that the reports of dinosaur remains in strata "above" the mammal-bearing beds are due to errors in stratigraphy in failure to recognize these conditions of deposition. There would indeed be no *a priori* improbability in the survival of dinosaurs in the isolated continent of South America after their extinction in the northern world; but the evidence that they did so seems open to very serious question.

APPENDIX B. UNCONFORMITY BETWEEN THE LARAMIE AND THE LANCE

"The asserted magnitude of the break between Laramie and Lance rests not on evidence but on a definition of the Laramie." This remark appears to require explanation, although the subject is outside the scope of this paper. The evidence for an "unconformity of 20,000 feet" is not, as one might suppose from Knowlton's repeated references to it, derived from measurements of the strata removed beneath an angular unconformity. It is based on the occurrence in the basal conglomerates of the Lance and equivalents of pebbles derived from the older formations of (presumably) the adjoining mountains. The *assumption* is made that the Laramie, along with the rest of the underlying formations, had extended over the area of these mountains and was upheaved, swept away by erosion, and the underlying formations cut down to the Paleozoic series, from which these pebbles are derived, during the interval between Laramie and Lance. But although Lee has reported evidence for such an extension of the older Cretaceous beds in New Mexico, there is no evidence that the Laramie had the same extension, save its definition as the "latest conformable member of the Cretaceous succession." It was to this circumstance that the remark had reference. It appears to me, on the other hand, that whatever inferences may have been made from

the definition, it is very improbable that the Laramie was coextensive with the original limits of the older Cretaceous formations. Between the Niobrara and Laramie there was a widespread and considerable uplift on the plains, probably much intensified along the mountain ridges, and the erosion due to the latter probably supplied the materials for the Laramie sedimentation, as their further uplift did for the subsequent continental formations of that region.

RECENT RESULTS IN THE PHYLOGENY OF THE
TITANOTHERES¹

BY HENRY FAIRFIELD OSBORN

(Read before the Paleontological Society December 31, 1913)

Recent discoveries have modified the author's earlier opinions as to the lines of descent of the titanotheres and still further changes are anticipated with increase of knowledge of the connections between Upper Eocene, or Uinta, titanotheres and those of the Lower Oligocene, or White River.

The main lines of division are indicated in the proportions of the limbs, whether cursorial, mediportal, or graviportal; the proportions of the skull, whether mesaticephalic, brachycephalic, or dolichocephalic; the development of fronto-nasal horns, whether accelerated or retarded; the molarization of the premolar teeth, whether accelerated or retarded; the presence or absence of incisor teeth; the abbreviate or elongate, the triangular or oval form of the fronto-nasal horns as developed in Oligocene times.

With these criteria the various phyla may readily be distinguished as follows:

A. Wind River titanotheres, face more elongate than cranium:

- | | |
|---|-----------------------------|
| I. Lambdotheriinae, light-limbed, cursorial. | Genus, <i>Lambdotherium</i> |
| II. Eotitanopinae, medium-limbed, mediportal. | <i>Eotitanops</i> |

B. Bridger and succeeding titanotheres, cranium longer than face:

- | | |
|--|--|
| III. Palaeosyopinae, short-limbed, brachycephalic. | Genus, <i>Palaeosyops</i> ,
<i>Limnohyops</i> |
| IV. Telmatheriinae, mesaticephalic to dolichocephalic. | <i>Telmatherium</i> ,
<i>Sthenodectes</i> |
| V. Diplacodontinae, dolichocephalic, with accelerated molarization of the premolars, imperfectly known. | <i>Diplacodon</i> |
| VI. Manteoceratinae, mesaticephalic to brachycephalic, accelerated development of the horns, mediportal. | <i>Manteoceras</i> ,
<i>Protitanotherium</i> |

¹ Manuscript received by the Secretary of the Geological Society June 15, 1914.

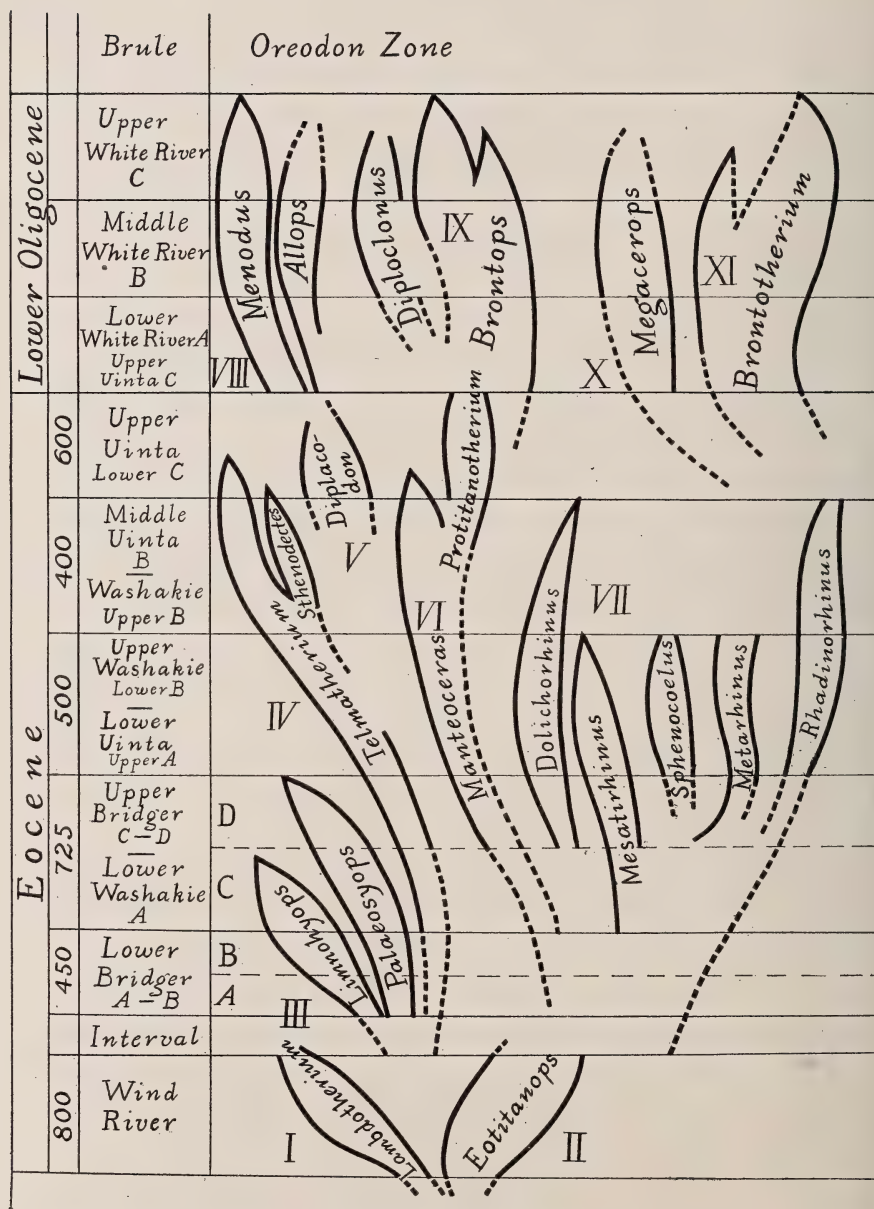


FIGURE 1.—Phylogeny of the Titanotheres as known to December, 1913

- | | |
|---|---|
| <p>VII. Dolichorhinæ, mesaticephalic to dolichocephalic, limbs, so far as known, abbreviate.</p> | <p><i>Dolichorhinus</i>,
 <i>Mesatirhinus</i>,
 <i>Sphenocælus</i>,
 <i>Metarhinus</i>,
 <i>Rhadinorhinus</i></p> |
| <p>VIII. Menodontinæ, mesaticephalic to dolichocephalic, with abbreviate, triangular horns, with incisor teeth reduced or wanting, feet and limbs elongate.</p> | <p><i>Menodus</i> (= <i>Titanotherium</i>),
 <i>Allops</i></p> |
| <p>IX. Brontopinæ, brachycephalic, horns abbreviated, rounded or oval, incisors persistent.</p> | <p><i>Brontops</i> (= <i>Megaceratops</i>),
 <i>Diploctonus</i></p> |
| <p>X. Megaceropinæ, mesaticephalic to extreme brachycephalic; horns elongate, vertically placed, no incisor teeth.</p> | <p><i>Megacerops</i>
 (= <i>Symborodon</i>)</p> |
| <p>XI. Brontotheriinæ, mesaticephalic to brachycephalic, horns elongate, transversely flattened and divergent.</p> | <p><i>Brontotherium</i></p> |

The free use of subfamily divisions to express the distinct phyletic series is similar to that which the author has adopted in the phylogeny of the rhinoceroses. More conservative usage would divide the titanotheres into four subfamilies only.

NEW METHODS OF RESTORING *EOTITANOPS* AND
*BRONTOTHERIUM*¹

BY HENRY FAIRFIELD OSBORN

(Read before the Paleontological Society December 31, 1913)

An advance in method based on very thorough study of the musculature of the Perissodactyla has been adopted in restoring *Eotitanops* and *Brontotherium* as representing the first and the last stage of this great family of titanotheres. Dr. W. K. Gregory assisted by Mr. Erwin Christman undertook an exhaustive research on the myology of the titanotheres based on the detailed studies of the anatomy of the horse and tapir by Schmalz, Murie, Windle, Parsons, and others. On this basis the superficial musculature of *Palaeosyops* and of *Brontops* has been almost completely restored, giving the special significance of all the areas of origin and insertion of the various muscles and tendons.

With this knowledge in hand, the restoration of *Brontotherium* was undertaken afresh and a very precise scale drawing of the skeleton of *Brontops robustus* was projected with the complete musculature. With these data the modeling of *Eotitanops*, a largely conjectural skeleton, and of *Brontops*, a fully known skeleton, was undertaken by Mr. Christman under the direction of the author. The result is a far more authentic restoration of both of these animals than any which has been attempted or published. Now that these typical perissodactyls have been restored in this thorough manner, the same muscle data and methods may be employed in the restoration of other perissodactyls with increasing approximation to the truth.

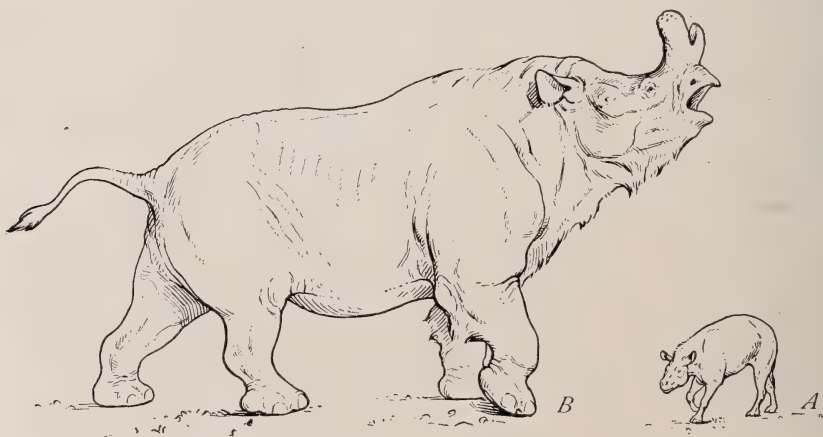


FIGURE 1.—First and last known Stages in the Evolution of the Titanotheres
Models by Erwin Christman, under direction of the author, December, 1913

¹ Manuscript received by the Secretary of the Geological Society June 15, 1914.

RESTORATION OF THE WORLD SERIES OF ELEPHANTS
AND MASTODONS ¹

BY HENRY FAIRFIELD OSBORN

(Read before the Paleontological Society January 1, 1914)

Under the author's direction the animal sculptor Mr. Charles R. Knight has been engaged during the past two years on a series of models of the elephants and mastodons to a uniform scale of $1\frac{1}{2}$ inches to the foot, or a one-eighth scale. Three living and three extinct types have been completed, and the series will finally include the ancestral proboscidian stages as far back as *Palæomastodon*, all to the same scale.

The standards of shoulder height of the recent forms are taken from the well known records of Rowland Ward (1907), and the estimates of shoulder height of extinct forms are taken partly from actual skeletons, as in the case of the mastodon and woolly mammoth, and from fore-limb measurements in the case of the imperial mammoth. These heights in descending order are as follows:

Imperial mammoth, *Elephas imperator*, 13 feet 6 inches, estimate of F. A. Lucas.

African elephant, *Loxodon africanus*, 11 feet $8\frac{1}{2}$ inches, record of Rowland Ward.

Indian elephant, *Elephas indicus*, 9 feet 10 inches, record of Rowland Ward.

Indian elephant, *Elephas indicus*, 10 feet 6 inches, record of Rowland Ward.

Hairy mammoth, *Elephas primigenius*, 9 feet 6 inches, estimated from skeleton.

American mastodon, *Mastodon americanus*, 9 feet 6 inches, estimated from skeleton.

Pigmy African elephant, *Loxodon cyclotis*, 6 feet 2 inches, present height of type specimen in New York Zoological Park.

The tusks in each type, which in these models are also record tusks as to length and curvature, are selected as the most generally characteristic in form and curvature or are actual tusks, as in the case of *L. africanus*, *E. primigenius*, and *E. imperator*. The living forms have been studied by Mr. Knight directly from types in the New York and other zoological parks. They are regarded by experts as excellent models except in the

¹ Manuscript received by the Secretary of the Geological Society June 15, 1914.

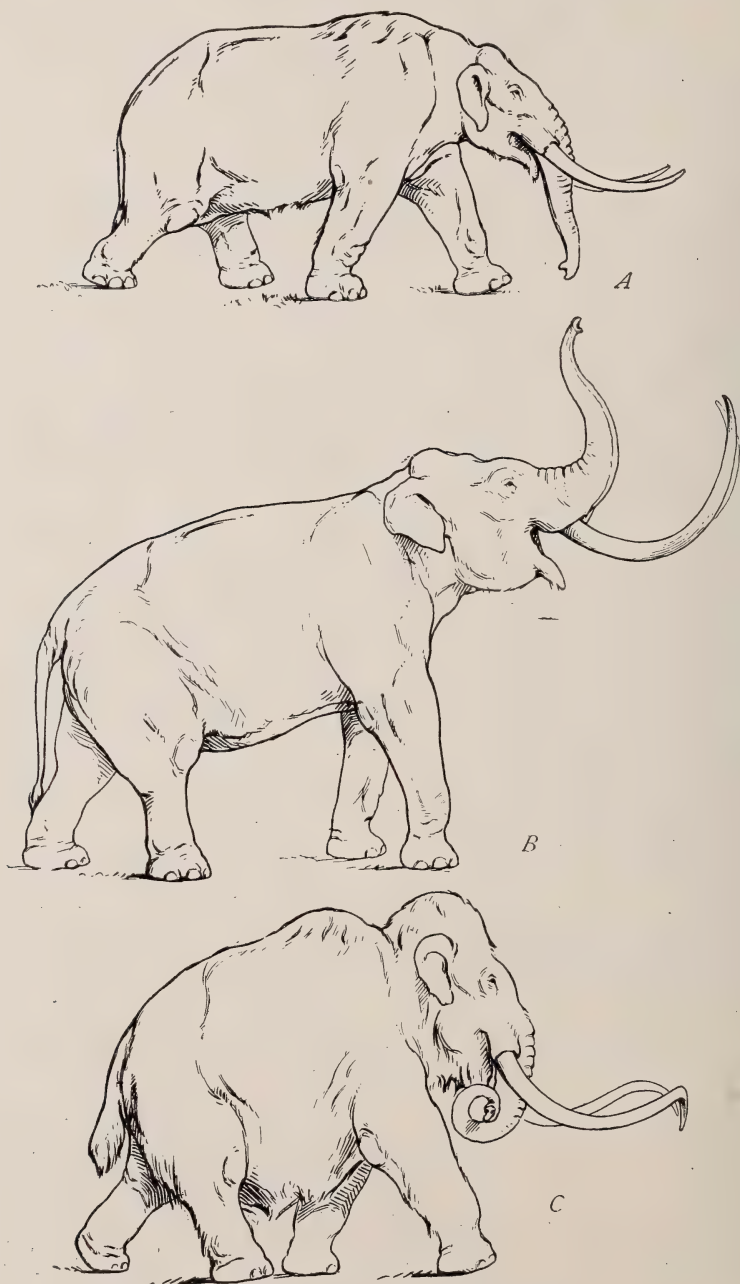


FIGURE 1.—Restoration of Mastodon and Elephants

A, American mastodon, *Mastodon americanus*; B, Imperial mammoth, *Elephas imperator*;
C, Woolly mammoth, *Elephas primigenius*. Models in the American Museum

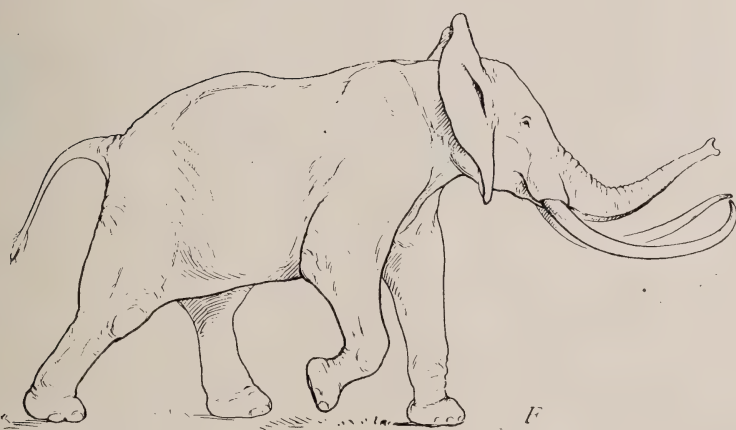
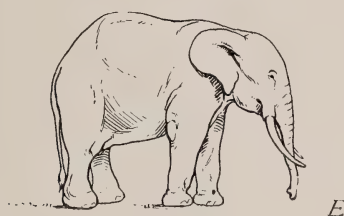
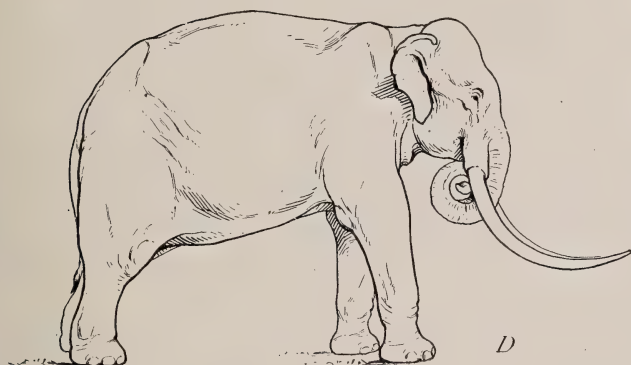


FIGURE 2.—Restoration of Elephants

D, Indian elephant, *Elephas indicus*; E, Congo elephant, *Loxodon cyclotis*; F, African elephant, *Loxodon africanus*. Models in the American Museum

proportions of the neck, which are far more massive and powerful than as represented by Mr. Knight in the African bull, for example. The mastodon is drawn very closely on the famous Warren mastodon skeleton in the American Museum of Natural History. The imperial mammoth

is almost entirely conjectural since the top of the skull has not yet been discovered, and it is not known, therefore, whether the animal had the characteristic peaked cranium of the true mammoth type, or the flattened cranium of the African type, or the bulbous cranium of the Indian type.

The hairy mammoth is by far the most probable restoration in the extinct series because it is based, first, on the complete skeleton, second, on the data furnished by the frozen Siberian mammoth, third, and most important, by the extraordinary likeness which prevails in all the numerous drawings, engravings, and sculptures of *E. primigenius* by the artists of Upper Paleolithic times.

In preparing these models we were at once struck by the highly distinctive differences in the contour not only of the forehead but of the backbone. The *L. cyclotis*, for example, while of diminutive size and with rounded ears, has the distinctive backbone profile of the African elephant, which is hollow between the shoulders and the hips. The backbone of the Indian elephant is uniformly arched upward; that of the mammoth rapidly falls away toward the hind quarters, and a similar character is doubtfully attributed to the imperial mammoth.

The extraordinary dome over the head of the woolly mammoth, separated by a deep valley from the dome over the back, is probably due to an accumulation of hair and wool and possibly to the presence of a storage reservoir of adipose tissue, because we know that this rounded form does not coincide at all with the peaked, flattened forehead of the skull within. For purposes of casting, the hair, which nearly touches the ground beneath the neck and belly of the mammoth and constitutes a uniform fringe around the lower part of the limbs, is reduced.

RECTIGRADATIONS AND ALLOMETRONS IN RELATION TO
THE CONCEPTIONS OF THE "MUTATIONS OF WAAGEN,"
OF SPECIES, GENERA, AND PHYLA¹

BY HENRY FAIRFIELD OSBORN

(Read before the Paleontological Society January 1, 1914)

CONTENTS

	Page
General discussion.....	411
Discussion of the illustrative diagrams.....	413
Space, geographic divergence, and evolution.....	414
Geographic distribution.....	416

GENERAL DISCUSSION

The new problem raised in this contribution is that of the comparison of a geologic ascending evolutionary series in time, like that of the titanotheres, with a contemporaneous geographic series of species, subspecies, and varieties which may be grouped within a single genus: In what respects do the characters observed in a genus ascending and developing in geologic time resemble or differ from the characters observed in a genus distributed in geographic space?

The superb materials assembled by Osborn with the cooperation of William K. Gregory for the study of the titanotheres enable us to determine with precision that in a *time series* there are two kinds of characters in the hard parts of mammals, namely, *allometrons*, or changes of proportion, and *rectigradations*, or the appearances of absolutely new characters. For example, a new cusp or a new horn rudiment is regarded as a rectigradation in its initial stage; but when it takes on profound changes of proportion in the course of evolution these changes are known as allometrons. These characters appear to evolve under a different combination of causes. The accumulation of allometrons and rectigradations marks the steps from "species" to "species" and the minute continuous

¹ Manuscript received by the Secretary of the Geological Society June 15, 1914.

species and varieties have been studied extensively by Merriam, Miller, Osgood, and other mammalogists, but the characters which have been used to distinguish them have not yet been analyzed in comparison with the characters which are employed by paleontologists to distinguish the ascending geologic mutations and species.

DISCUSSION OF THE ILLUSTRATIVE DIAGRAMS

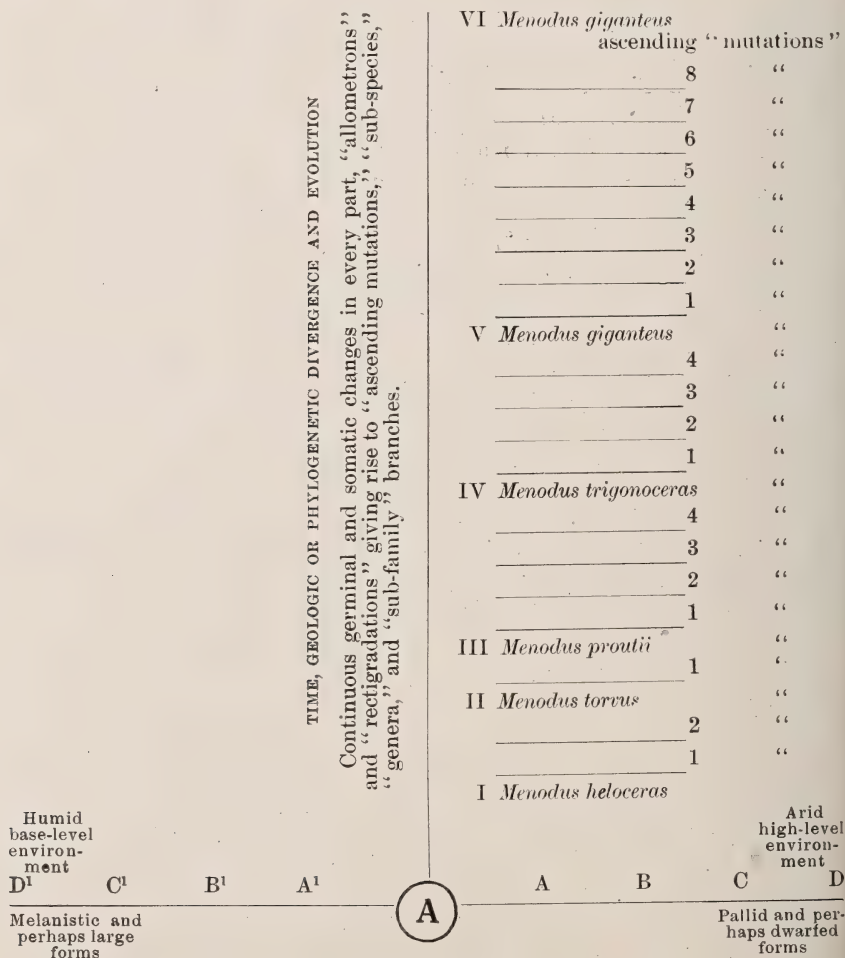
The accompanying diagrams present in graphic form this future problem for the cooperation of the zoologist and paleontologist who have made observations independently hitherto without comparison of their separate results. The very circumstance that these facts have been garnered independently by workers in two fields of observation, with no purpose but the *close definition and distinction of nearly related forms*, renders all the more valuable any results which may be obtained in the future. In other words, the facts have been garnered both in zoology and vertebrate paleontology without that bias or preconceived theory which often influences us to observe some facts rather than others.

The problem of this comparison between zoologic and paleontologic series is complicated by the fact that all zoologic series which are of wide geographic range must necessarily be widely separated *in time* as well as *in space*. For example, the genus *Peromyscus* as studied by Osgood (1909) presents a continuous series of transitions in color and form from the types which we observe on the Isthmus of Tehuantepec to those we observe in Alaska. In the northerly region we find a larger animal, with a relatively longer tail and a skull which may be somewhat longer or more dolichocephalic. The genus *Perognathus* offers better examples of skull change in connection with geographic distribution, for instance, in the form of the interparietal bone. The wide distribution of *Peromyscus* may have taken place from some common center during post-Glacial time, that is, during the last 20,000 years. In this period there has been both a *space evolution* and a *time evolution*, the latter being comparable to that which would be observed in a geologic series. This principle is clearly brought out in the accompanying diagram, in which A represents the stem or central form from which the geographic races have been given off, which in course of time, undergoing an evolution in time of from 5,000 to 40,000 years, diverge from the parent form (A) precisely like the geologic or time series. Forty thousand years may have elapsed since a geographic species or subspecies separated off from the parent form. Even in geologic estimates 40,000 years is an appreciable interval, in which new allometrons may arise and new rectigradations may appear.

TABLE II.—*Contrast between space evolution (geographic) and time evolution (geologic) from a central or stem form A*

A I–VI is an actually recorded series of ascending “Mutations of Waagen” and “species,” assembled in the “genus” *Menodus*.

A–D and A¹–D¹ are hypothetical geographic varieties, *et cetera*, of *Menodus*, which probably existed in Lower Oligocene times for the “genus” is now known to have ranged geographically from South Dakota to the vicinity of Prag, Bohemia (*Menodus bohemicus*).



SPACE, GEOGRAPHIC DIVERGENCE, AND EVOLUTION

Somatic changes rapid and conspicuous; germinal changes gradual

Environmental (ecologic) and ontogenetic (habitudinal) influences producing divergent somatic effects on animals of similar ancestral stock, “environ-

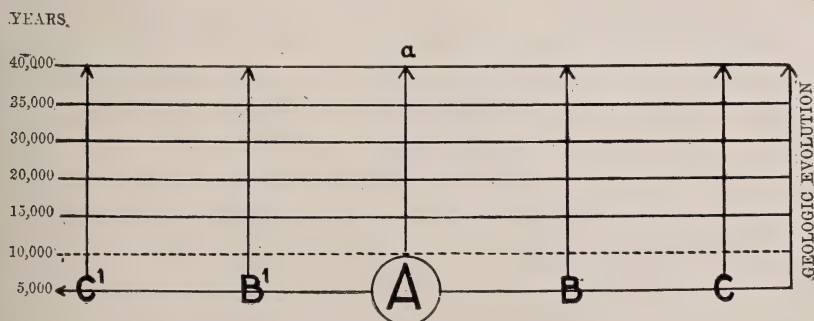
mental or ontogenetic species," "sub-species," "races," "varieties," distinguished by different coloring, habits, proportions ("allometrons"), and perhaps by "rectigradations."

It follows that to institute a true comparison between a geographic series and a geologic series precisely the *same methods of observation* should be employed. Direct measurements of length and breadth should be recorded from which *indices* (proportions of single structures like the skull) and *ratios* (proportions between different parts like the upper and lower segments of limbs) should be established.

It is already known that allometrons, or changes of proportion, in every part distinguish the various geographic species and subspecies of *Ursus*, for example, as studied by Merriam, the changes technically known as dolichocephaly, brachycephaly, dolichopy (or elongation of the face), brachyopy (abbreviation of the face), brachypody (abbreviation of the feet), dolichopody (elongation of the feet), brachymely (abbreviation of the limbs), dolichomely (elongation of the limbs), occur in zoologic series *in their incipient stages* exactly as they occur in paleontologic series. The only distinction is that in paleontologic series they may be followed through vastly greater periods of time in all the stages from incipency to the various climaxes.

For example, the ten phyla of titanotheres described in the preceding contribution are distinguished by progressive changes of proportion in different directions. Thus one phylum is progressively brachycephalic until it reaches an extreme in which the breadth of the head is as great as the length; another phylum is progressively dolichocephalic until the head reaches a long, attenuated form.

TABLE III.—Showing that geographic or space distribution and geologic or time distribution may take place coincidently from a central stem form **A** during such an epoch as the post-Glacial.



GEOGRAPHIC DISTRIBUTION

Whether the causes of these changes are to be sought in heredity or ontogeny or environment or selection, or in the interactions of these four coefficients of evolution, is a problem which remains obscure to the paleontologist working in paleontology alone; but it may be illuminated by the combined observations of the paleontologist and the zoologist in cooperation, as proposed in this paper. The zoologist has already demonstrated that there is direct relation between certain types of coloration and environment, as well as between certain habitats and harmonic increase or decrease in size; it remains to be determined, chiefly by the zoologist, whether certain environments induce uniformly similar allometrons. Our present evidence indicates that this is not the case. Anthropologists have failed, for example, to establish any definite relation between environment and human head form. Again, the selection-value of allometrons, or changes of proportion, is obvious in certain cases, but not at all apparent in others. Gerritt S. Miller also fails to observe any direct relation between environment and head proportion, although an indirect relation may arise in connection with differences of food and feeding habits in different environments.

The author has already (May, 1914) been promised the cooperation of a number of eminent mammalogists in a comparison of zoologic² with paleontologic data which may be fruitful of important results.

² Gerritt S. Miller (May, 1914) observes that there are abundant illustrations of the direct action of environment on color in mammals, but that as to proportions, size, and cranial characters the case is quite different. In other words, there are plenty of instances of color changes of different character affecting many different members of a fauna in the same way, as when we pass from a wet to a dry climate or from a low to a high altitude, but there do not appear to be any parallel set of changes in proportions, size, or structure.

GEOLOGY OF THE UINTA FORMATION¹BY EARL DOUGLASS²

(Presented before the Paleontological Society by H. F. Osborn January 1, 1914)

CONTENTS

	Page
Introduction.....	417
Extent and location of the formation.....	418
Divisions of the deposits.....	418

INTRODUCTION

The deposits here discussed were called the "Uinta Group" by Clarence King in 1878.

The great thickness of reddish sandstones and quartzites of the Paleozoic of the Uinta Mountains were previously, in 1878, named "Uinta" by Powell. It is best, therefore, at present to designate the deposits now under discussion as the "Uinta Group" or the "Uinta Tertiary."

The Uinta Tertiary has furnished many interesting mammalian and reptilian remains, and several expeditions have been sent into the Uinta Basin to collect fossils. Some of these show that at least part of these deposits are newer than the typical Bridger and older than the White River Oligocene; therefore the name of the group has given the name to a stage in the development of vertebrate life called the "Uinta stage."

The main area containing the Uinta Group is quite extensive, but lies in one compact body and the boundaries, as a rule, are quite well defined. It furnishes an excellent area for the study of Upper Eocene geology; but there never has been a careful survey of the region, nor has there

¹ Manuscript received by the Secretary of the Geological Society June 15, 1914.

² Introduced by H. F. Osborn.

ever been published a detailed geological section of any portion of it. The present government geological survey, which has done some work in adjacent coal-bearing and oil-bearing formations, has left some phases of the geology of the Uinta in greater confusion than before.

Mr. O. A. Peterson was the first and almost the only geologist to give us an outline of the subdivisions of the Uinta Group and to furnish a true basis for more detailed work. Prof. E. S. Riggs has added very valuable observations on the lithological characters and on the occurrence of fossils in the lower portions of the deposits.

Until the large amount of vertebrate material which has been collected at various times by O. A. Peterson and Earl Douglass, which is now being prepared for study in the Carnegie Museum, has been studied in connection with sections and extensive field notes, only a provisional outline of the geological conditions and their significance can be given; but it is hoped that this brief outline of section of the Uinta will supply some long desired and such needed light on this interesting group.

EXTENT AND LOCATION OF THE FORMATION

The lower portions of these deposits may be, and probably are, contemporaneous with portions of deposits in the Bridger and Washakie basins and with other deposits elsewhere. But these beds from the Green River formation up to the superficial deposits, which in some places overlie them at the foot of the Uinta Mountains, will for the present be treated under the old name "Uinta Group;" but it must be borne in mind that it is probably only the upper portion which belongs to the distinctive "Uinta stage."

The Uinta Tertiary deposits are in Uinta and Wasatch counties, Utah. The extreme extent is something like 75 miles east and west and 40 miles north and south. They occupy a large portion of the Uinta Basin in the southern base of the Uinta Mountains.

DIVISIONS OF THE DEPOSITS

The deposits were divided by Peterson into A (lower), B (middle), and C (upper) Uinta.

Uinta "A" occupies the southern portion of the area. The lower portion of "A," on White River at Wagonhound Canyon, is about 585 feet in thickness. No determinable mammalian remains have been found in it,

but there is much fossil wood, and there is one band of shale which contains fossil leaves and insects, which implies a temporary return of conditions under which the underlying Green River beds were deposited. The beds below this band of shale, however, are very puzzling and their mode of deposition difficult to explain. So it is doubtful whether the lower 170 feet of this section should be placed with the Green River, Uinta A, or in a separate transitional formation by itself. If we take away this portion of the section it would leave only 415 feet as the thickness of Lower A.

The upper portion of Uinta "A" is somewhat fossiliferous at several levels, containing remains of Uintatheres, Titanotheres, and other mammals; also turtles and unios. Much of the best material collected by Riggs came from these beds and Mr. Peterson made a valuable collection from them in 1912. They are 270 feet thick.

The total thickness of Uinta "A" is, therefore, from 685 to 855 feet thick, depending on whether we place the lower 170 feet in the Uinta of Green River.

Uinta "B" is about 420 feet in thickness. In these beds there is a less proportion of heavy river sandstones and more sandy shales and clays, which are green, gray, and red.

From these beds came a large proportion of the collections of vertebrates made by Peterson for the American Museum of Natural History and the later collections made by Douglass for the Carnegie Museum. The latter was made from perhaps 20 or more levels, and so far as possible records were made, so that the fossils can be referred to their proper horizons.

Uinta "C" was measured farther to the westward, beginning about 2 miles east of Cottonwood Grove, on White River, near the Uinta Stage Line, and proceeding in a direction west of north to the highest exposure on Dead Man's Bench, about 16 to 18 miles south of Vernal. This included about 1,440 feet of strata. The beds here, as in most other portions of the deposits, were dipping at an angle of 3 degrees or more to the northwestward. Lying to the northwestward across Green River were mesas and benches of Uinta deposits, apparently several hundred feet in height and evidently lying higher geologically than the geological base on which we stood. The total thickness of Uinta "C" is apparently not less than 2,000 feet.

The total measured thickness of the Uinta Group here is 2,275 feet, exclusive of the 170 feet at the bottom. The original thickness was probably not less than 3,000 feet.

With regard to the subdivisions of the Uinta, Mr. Peterson and Mr. Douglass have discussed the matter together and with Professor Osborn, and the latter has gone over the matter with Mr. Riggs, and there appears to be an agreement as to the dividing line between Lower and Upper "A" and between "A" and "B." Though the exact division line between "B" and "C" has not been fixed with certainty, Peterson and Douglass agree as to where it should be placed provisionally.

CAMBRIAN AND RELATED ORDOVICIAN BRACHIOPODA—
A STUDY OF THEIR INCLOSING SEDIMENTS¹

BY LANCASTER D. BURLING

(Read before the Paleontological Society January 1, 1914)

CONTENTS

	Page
Introduction.....	421
Previous work.....	422
Number of species and varieties occurring in the different types of sediment.....	423
Genera and subgenera identified from but one type of sediment.....	427
Lithologic, stratigraphic, and geographic range compared.....	428
Data as to inclosing sediment classified and compared.....	429
<i>a.</i> For species occurring more than once in the same section.....	429
<i>b.</i> For all species occurring more than once.....	429
Number of localities and number of species per locality in the different types of sediment.....	431
Summary.....	433

INTRODUCTION

In his work on the Cambrian and related Ordovician Brachiopoda the writer has had access to approximately 1,350 of the Cambrian fossil localities represented in the collections of the United States National Museum,² from about 72 per cent of which, or 975, brachiopods have been identified. All of this material and all known references to the occurrence of Cambrian Brachiopoda throughout the world were utilized in this study of the nature of their inclosing sediments, an investigation which was first suggested by Professor Schuchert in a letter to Mr. Walcott, and seemed to be justified by the abundance of the material, its

¹ Manuscript received by the Secretary of the Geological Society April 10, 1914.

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² This represents only the number which were available for the work on Monograph 51 of the U. S. Geological Survey on the Cambrian Brachiopoda. The collections of Mr. E. O. Ulrich contain many brachiopods from the Cambrian, as that term is usually defined.

variety, and the magnitude of its geographic range. The present report is based on the study of 44 genera, 15 subgenera, 477 species, and 59 varieties of Cambrian Brachiopoda, and 3 genera, 1 subgenus, 42 species, and 1 variety of exclusively Ordovician Brachiopoda from 1,460 localities within the national boundaries of 16 countries. The United States is represented by collections from 28 States, Canada by localities in eight of her provinces, and among the continents of the world Africa alone is unrepresented.

The sediments were divided into three classes (limestone, shale, and sandstone) and the following tables were prepared: (1) By genera and subgenera, giving the number of species of each identified from the different sediments;³ (2) by genera and subgenera, listing only those groups which appear to be confined to one type of sediment and giving the number of species of each and the number of localities from which they have been identified; (3) by types of sediment, classifying the mutual relationships between the several horizons of species occurring more than once in the same section; (4) by character of gradation shown between the horizons of all species occurring more than once, and (5) by three arbitrary groups, giving the number of localities and the number of species per locality in each of the three classes of sediment.

PREVIOUS WORK

Foremost among previous investigations of a similar character is the exhaustive work of Bigsby.⁴ Based on (*a*) general divisions into calcareous and non-calcareous sediments and (*b*) minute discriminations, recognizing 10 or 12 different types of sediment, his results can not be directly compared with those in this paper, but the following figures may be of interest: "The calcareous or deep-sea sediments are much more fossiliferous than the arenaceous or shallow bottoms, being as eight to one [823 to 102 (page 264)] in New York and two to one [1,003 to 724 (page 264)] in Wales" (page 260). "Most of the genera of Brachiopoda furnish examples of arenicolous and argillicolous species" (page 262). "Of 254 species of Brachiopoda in New York, of known matrix, only 24 [24 out of 237 (page 264)] are found in non-calcareous sediments; whilst in Wales the distribution is much more general, there being 207 appearances in the beds just spoken of, against 309 in the limestone rocks" (page 262). Dividing the sediments into groups necessitating a

³A preliminary draft of this table was incorporated in Cambrian Brachiopoda, Monogr. U. S. Geol. Survey, vol. II, pt. 1, 1912, by Charles D. Walcott, p. 160.

⁴Quart. Jour. Geol. Soc. London, vol. 15, 1859, pp. 251-335: Part III.—An inquiry into the sedimentary and other external relations of the Paleozoic fossils of the State of New York.

discrimination between "calcareous argillaceous shale" and "argillo-calcareous shale," for example, and applying the term divergents to those species which are not constant to single units of this character but deviate into others, he secures the following figures (page 269): Of the 766 known Welch species, 380, or 49 per cent, are divergents; of the 167 known Welch Brachiopoda, 114, or 68 per cent, are divergents; of the 841 known New York species, 93, or 11 per cent, are divergent, and of the 225 known New York Brachiopoda, 18, or 8 per cent, are divergent. He considers the figures for the American area as "an inadequate estimate of the true divergence" (page 267). The apparently complete lack of correlation between the different figures given by Bigsby in his exhaustive compilation would seem to indicate a source of error which is probably attributable to the attempt to carry to so fine a degree of minuteness statements by many different authors as to the nature of the inclosing sediment. Furthermore, determinations based on statements as to the lithologic character of the formation from which a species has been identified have not proven to be dependable, since a shale series may contain thin interbedded limestones filled with their own peculiar fauna.

NUMBER OF SPECIES AND VARIETIES OCCURRING IN THE DIFFERENT TYPES OF SEDIMENT

Table I was compiled from a list⁵ of all the species and varieties of Cambrian and related Ordovician Brachiopoda described in Monograph 51 of the United States Geological Survey, giving the number of times each has been identified from each of the three classes of sediment—for example, *Lingulella ferruginea* was recognized in 25 faunules, of which 9 were in limestone, 13 in shale, and 3 in sandstone; *Obolus apollinis* was recognized in 23 faunules, all of them being in sandstone; etcetera, etcetera. Subtracting from the total number of species and varieties included in this list (579) the species for which we have no data as to the inclosing sediment (24), we obtain 555 species, of which 412, or 74 per cent, have been identified from but one type of sediment. This number (412) includes 218 species that have been identified from one locality only, a fact which, under the conditions governing the separation into localities, precludes their identification from more than one type of sediment. The elimination of this number causes the percentage of species identified from but one type of sediment to fall to 35, a figure still sufficiently high, in view of the restrictions under which it was secured, to indicate the pronounced influence of the character of the sea-bottom on the distribution of the brachiopodous species.

⁵ This list covers 25 manuscript pages, and the figures for the individual species do not appear to be important enough to justify its inclusion in this paper.

TABLE I.—*Genera and subgenera of Cambrian and related Ordovician Brachiopoda, giving number of species and varieties occurring in the different types of sediment*

Genera and subgenera	Limestone.		Shale.		Sandstone.		Limestone and sandstone.		Limestone and shale.		Shale and sandstone.		All three.
	Ex- clusive.	Total.	Ex- clusive.	Total.	Ex- clusive.	Total.	Ex- clusive.	Total.	Ex- clusive.	Total.	Ex- clusive.	Total.	
<i>Acrotheca</i>	9	17	16	28	4	9	0	1	7	8	4	5	1
(<i>Redlichella</i>)	1	1	...	...	...	...	...	...	...	...	...	...	...
<i>Acrothyra</i>	1	1	1	3	2	4	...	...	...	...	2	2	...
<i>Acrothra</i>	30	47	10	26	8	15	3	5	12	14	2	4	2
<i>Bicia</i>	2	2	...	...	...	...	...	...	...	...	...	...	...
<i>Bilingsella</i>	9	15	2	5	4	9	3	5	1	3	...	2	2
<i>Botsfordia</i>	1	2	1	1	1	2	1	1	...	...	...	...	...
<i>Clarkella</i>	1	1	...	...	...	...	...	...	...	...	...	...	...
<i>Clarticia</i>	...	...	...	...	1	1	...	...	...	...	...	...	...
<i>Dearbornia</i>	1	1	...	...	...	...	...	...	...	...	...	...	...
<i>Delgadella</i>	...	...	1	1	...	...	...	...	...	...	...	...	...
<i>Dicelomus</i>	1	6	0	3	0	4	2	4	1	3	0	2	2
<i>Dicrinolepis</i>	...	...	...	...	1	1	...	...	...	...	...	...	...
<i>Discinopsis</i>	1	1	...	...	1	1	...	...	...	...	...	...	...
<i>Elkania</i>	2	2	1	1	...	...	...	...	...	...	...	...	...
<i>Eoorthis</i>	19	23	7	9	5	7	2	2	2	2	...	...	...
<i>Eostrophomena</i>	1	1	...	...	...	...	...	...	...	...	...	...	...
<i>Finkelburgia</i>	...	...	...	...	3	3	...	...	...	...	...	...	...
<i>Helmersenia</i>	...	...	...	...	1	1	...	1	...	...	...	...	...
<i>Huenella</i>	7	8	...	...	0	1	1	1	...	...	...	...	...
<i>Keyserlingia</i>	...	...	...	...	1	1	...	...	...	...	...	...	...
<i>Kutorgina</i>	2	4	0	3	1	2	...	...	2	2	1	1	...
<i>Lingulella</i>	16	35	19	36	21	36	6	11	8	13	4	9	5
(<i>Leptembolus</i>)	...	...	...	...	1	1	...	...	...	...	...	...	...
(<i>Lingulepis</i>)	4	5	3	7	5	9	0	1	0	1	3	4	1

<i>Linnarssonella</i>	2	7	0	4	0	2	5	1	2	3	4	0	1	1	1
<i>Mickwitzia</i>	5	9	1	4	5	5	1	1	1	3	3	5	1	1	1
<i>Macromitra</i>	4	5	2	3	0	1	1	0	1	0	1	0	1	1	1
(<i>Ipheidella</i>)	6	13	4	9	2	7	7	2	5	2	5	0	3	3	3
(<i>Paternia</i>)							1					1			
<i>Neobolus</i>							2	0	2	0	2	0	2	2	2
<i>Nisus</i>	3	5	1	3	0	2	4	4	2	3	3	1	2	1	1
(<i>Jamesella</i>)	7	10	0	3	4	4	7	1	2	0	1	1	2	2	2
<i>Obolella</i>	4	6	1	3	4	1	1								
(<i>Glyptias</i>)							29	6	9	5	8	0	3	3	3
<i>Obolus</i>	21	35	10	18	20	1	1	1	1	1	1	1	1	1	1
(<i>Acritis</i>)	1	2	0	1	0										
(<i>Bröggeria</i>)	0	1	0	1	0		1	1	1	1	1				
(<i>Fordinia</i>)	2	3			0	0	2	2	2						
(<i>Lingulobolus</i>)	0	2			0	1	1								
(<i>Mickwitzella</i>)					0	2	2					2	2	2	2
(<i>Palaeobolus</i>)			0	2	4		4								
(<i>Schmidtia</i>)					10		14	2	3	1	2	1	2	1	1
(<i>Westonia</i>)	4	8	3	6	1	3	3					2	2	2	2
<i>Orbiculoidea</i>			0	2	1	1	1	0	1	0	1	0	1	1	1
<i>Orusia</i>	3	4	0	1	0		1								
<i>Otusia</i>	1	2					1	1	1						
<i>Philhedra</i>	1	1					1								
<i>Proforthis</i>	1	2	4	5			2	0	1	0	1	0	1	1	1
(<i>Loperia</i>)															
<i>Quebecia</i>	1	1			1	1	1	1							
<i>Rustella</i>			1	1	1		1								
<i>Schizambon</i>	2	2	1	1	1	1	1								
<i>Schizopholis</i>					1		1								
<i>Schuchertina</i>	1	1	1	1											
<i>Siphonotreta</i>	2	2	1	1											
<i>Sicantonia</i>			2	2											
<i>Syntrophia</i>	8	10			2	4	4	2	2			0	1	1	1
<i>Trenatobolus</i>	0	1	0	1	3		4	0	1	0	1	0	1	1	1
<i>Volborthia</i>	1	1		1											
<i>Wimanella</i>	1	2	3	4	1		1			1	1				

TABLE I.—*Genera and subgenera of Cambrian and related Ordovician Brachiopoda*—Continued

Genera and subgenera.	Limestone.		Shale.		Sandstone.		Limestone and sandstone.		Limestone and shale.		Shale and sandstone.		All Three.
	Ex-clusive.	Total.	Ex-clusive.	Total.	Ex-clusive.	Total.	Ex-clusive.	Total.	Ex-clusive.	Total.	Ex-clusive.	Total.	
<i>Wynnia</i> .....	....	....	1	1	....	....	....	....	....	....	....	....	....
<i>Yorkia</i>	2	3	....	....	1	2	1	1	....	....	....	....	....
Genera and subgenera	8	44	3	33	13	48	1	26	1	22	1	18	16
Species and varieties	191	310	96	198	125	214	39	67	52	80	22	50	28

NOTE.—The exclusive and total sections into which the sediment columns have been divided may be explained in this way: Of the 17 species of *Acrothele* that have been found in limestone, only 9 are confined to that sediment, 7 occurring in both limestone and shale and 1 in all three (limestone, shale, and sandstone); similarly the 28 species found in shale are made up of 16 that are confined to shale, 7 occurring in both limestone and shale, 4 occurring in shale and sandstone, and 1 in limestone, shale, and sandstone.

GENERA AND SUBGENERA IDENTIFIED FROM BUT ONE TYPE OF SEDIMENT

In the following table are listed the twenty-six genera and subgenera which have been identified from but one type of sediment. In all they form 41 per cent of the total number of these larger groups which have been recognized, but they include within their number twelve genera which are represented only by single species in single faunules. Of the more or less cosmopolitan genera, therefore, only 14 (or 22 per cent) appear to be confined to one type of sediment.

TABLE II.—*Genera and subgenera of Cambrian and related Ordovician Brachiopoda identified from but one type of sediment, giving numbers of species and localities.*

Genera and subgenera, those represented by single species in single faunules being placed in this column only, together with a statement as to the inclosing sediment.	Inclosing sediment.			Number of species in each genus.	Total number of localities from which these species have been identified.
	Limestone.	Shale.	Sandstone.		
<i>Acrothele</i> (<i>Redlichella</i>) (limestone)					
<i>Bicia</i>	×			2	6
<i>Clarkella</i> (limestone)					
<i>Curticia</i> (sandstone)					
<i>Dearbornia</i> (limestone)					
<i>Delgadella</i> (shale)					
<i>Discinolepis</i>			×	1	2
<i>Eostrophomena</i>	×			1	2
<i>Finkelburgia</i>			×	3	21
<i>Helmersenia</i>			×	1	3
<i>Keyserlingia</i>			×	1	3
<i>Lingulella</i> (<i>Leptembolon</i>)			×	1	6
<i>Mickwitzia</i>			×	5	18
<i>Neobolus</i>			×	1	3
<i>Obolella</i> (<i>Glyptius</i>)			×	1	2
<i>Obolus</i> (<i>Mickwitzella</i>)			×	1	13
<i>Obolus</i> (<i>Schmidtia</i>)			×	4	37
<i>Philhedra</i> (limestone)					
<i>Protorthis</i> (<i>Loperia</i>) (sandstone)					
<i>Quebecia</i> (limestone)					
<i>Schizopholis</i> (sandstone)					
<i>Schuchertina</i> (limestone)					
<i>Siphonotreta</i> ⁶	×			2	23
<i>Swantonia</i>		×		2	2
<i>Volborthia</i> (limestone)					
<i>Wynnia</i> (shale)					
Totals for limestone	3	.....	.....	5	31
Totals for shale		1	.....	2	2
Totals for sandstone			10	19	108

⁶ In Monograph 51 of the U. S. Geological Survey on the Cambrian Brachiopoda a poorly preserved Lower Cambrian shale species is very tentatively referred to this typically Ordovician genus under the name of *Siphonotreta* ? *dubia*, but it is from a single faunule and is described by Mr. Walcott as probably representative of a new type.

Of the twelve genera and subgenera represented by single species in single faunules, 7 occur in limestone, 2 in shale, and 3 in sandstone. For the fourteen more widely distributed genera the following discussion of the results embodied in the table may be of interest: One genus is confined to *shale*, but the two species of which it is composed are confined to single faunules. The apparently isolated examples of *Bicia* and *Eostrophenomena* from *limestone* might likewise be dismissed if it were not for the inclusion of *Siphonotreta*,⁷ a genus which is typically represented by two species from 23 localities. Three genera are thus not only confined to limestone, but are represented, in the case of *Bicia* and *Siphonotreta* at least, by a sufficient number of localities to render noteworthy their affinity for calcareous sediments. The genera and subgenera which appear to be confined to *sandstone* have been recorded largely from single geologic provinces; but these regions have been extensively studied and the figures are large enough to be convincing, if indeed they do not prove a marked preference on the part of several of these generic groups for an arenaceous habitat. Thus ten genera and subgenera, represented in the collections at our disposal by 19 species from 108 localities, appear to be confined to sandstone.

LITHOLOGIC, STRATIGRAPHIC, AND GEOGRAPHIC RANGE COMPARED

Species common to different sediments are shown on analysis to exhibit a more or less similar latitude in their stratigraphic range; to be exact, 44 per cent of the species occurring in more than one type of sediment (141) have been identified from more than one of the three main divisions (Lower, Middle, and Upper) of the Cambrian.

By a similar analysis it can be shown that there is a still closer relationship between lithologic and geographic range. Thus of the 141 species common to different sediments, 89 (or 63 per cent) have been collected from more than one State, province, or country, the number of such units ranging from 2 to 18, with an average of over 4; and of the 89 species just mentioned, 49 (or 55 per cent) appear to be common not only to four or more of these artificial units, but also to separable geologic provinces.

⁷ See the footnote to *Siphonotreta* on the preceding page.

DATA AS TO INCLOSING SEDIMENT CLASSIFIED AND COMPARED

A. FOR SPECIES OCCURRING MORE THAN ONCE IN THE SAME SECTION

TABLE III.—Table classifying the sediment data for species occurring more than once in the same section

Type of gradation in passing from older to younger strata.	Number of species showing gradation.	Number of species occurring in both facies of interbedded series.	Number of species occurring at approximately same horizon, records indefinite.
Shale to limestone.....	12	10	7
Limestone to shale.....	4		
Limestone to shale to limestone...	4		
Sandstone to limestone.....	7	2	4
Sandstone to shale.....	6	2	0
Shale to sandstone.....	4		
Sandstone to shale to sandstone...	2		
Limestone, shale, and sandstone...	0	0	0

Perhaps the most interesting features of the preceding table are (*a*) the fact that no discovered species of Cambrian Brachiopoda is in any one section common to limestone, shale, and sandstone; (*b*) the pronounced affinity of single species for both facies of an interbedded series composed of shale and limestone; and (*c*) the relatively high percentage of species able to accommodate themselves to a vertical change from sandstone to limestone and the absence of any species exhibiting the reverse progression.

B. FOR ALL SPECIES OCCURRING MORE THAN ONCE

TABLE IV.—Table classifying the sediment data for all species occurring more than once

Type of gradation in passing from older to younger strata.	Number of species occurring in the same section.	Number of species occurring in adjacent sections.	Number of species occurring in the same province.	Number of species occurring in different provinces.
Coarse to fine.....	31 ^s	15	10	5
Fine to coarse.....	14 ^s	4	2	1
Total showing gradation.	45	19	12	6
Total actually or apparently occurring in different sediments of the same age....	25	6	32	20

^s The four limestone-shale-limestone and the two sandstone-shale-sandstone gradations of Table III are credited to each of these figures; their elimination leaves the ratio of coarse-fine to fine-coarse, as 25 to 8.

The apparent synchronicity of (1) the inauguration of major stratigraphic units, (2) the introduction of new and temporarily persistent organic types, (3) the expansion of sea areas, and (4) the successive deposition of finer sediments supports the tabular indication that the majority of the species which appear to have been able to accommodate themselves to changes in the character of the sea-bottom are the ones accompanying gradations from the more clastic to the less. The figures for the more widely scattered occurrences (columns 3, 4, and 5) are naturally less significant than those for individual sections (column 2), but they appear to be corroborative, and thus bear evidence of a certain dependability. Even with a due appreciation of the uncertainties involved, we appear to be justified in assigning to the figures of this table and to those of Table III a more than coincidental origin.

NUMBER OF LOCALITIES AND NUMBER OF SPECIES PER LOCALITY IN THE
DIFFERENT TYPES OF SEDIMENT

TABLE V.—*Groups of Cambrian and related Ordovician Brachiopoda giving the number of localities and the number of species per locality in the different types of sediment.*

Groups.	Number of localities.				Average number of species per locality.		
	Total.	Shale.	Sand-stone.	Lime-stone.	Shale.	Sand-stone.	Lime-stone.
A.—Locality Nos. 1-300 (U. S. National Museum)	703	192	189	322	2.15	2.77	2.81
B.—Locality Nos. 300-396z (Literature)	642	170	241	231	1.55	1.70	1.73
C.—Chinese localities	35	12	0	23	1.75	0	1.96

The groups into which this table has been divided require a word of explanation. Group **A**, numbers 1 to 300, includes collections that have been made by members of the United States Geological Survey and the United States National Museum at various times and under differing conditions since the organization of the museum. With few exceptions each represents a distinct faunule, definitely numbered, and all of the brachiopods were culled for the work on the Cambrian Brachiopoda. Group **B**, numbers 300 to 396z, represents miscellaneous collections in the United States National Museum to which locality numbers have never been assigned and occurrences mentioned in the literature. The numbers have been arbitrarily assigned, there is no certainty that each number represents a distinct faunule, and in the case of the localities taken from the literature there is hardly the probability that all of the brachiopods occurring at each of the localities were described. Group **C**, the collections made by the Carnegie Institution of Washington Expedition to China, is probably the best of the three for the purposes of this study, since all of the collections were made by one man, under more or less similar conditions, during a single field season; yet sandstones are entirely unrepresented. Moreover, the forms from each of the groups (Group **B** containing the only specific occurrences that have not been checked by actual examination of the specimens themselves) have been studied under more or less uniform conditions by the same specialists. Among these three groups there appears to be no uniformity of ratio between the number of localities in each of the three classes of sediment and the total number included in the group. For the first two groups

the percentage of shale localities is 27, but the non-accordance of the other percentages would place this as a mere coincidence. Perhaps the most noticeable feature is the uniformity in the figures for each of the types of sediment; in fact the figures were so general that they were believed to indicate little or nothing until the study of the number of species per locality was completed. This number varied from 1 to 15 in both sandstone and limestone and from 1 to 13 in shale, and the averages for the groups betrayed so little evidence of system that the ratio between them was computed. Thus the ratio between the number of species per locality in shale and limestone for Group C is .892 ($\frac{1.75}{1.96}$); for Group B it is .896 ($\frac{1.55}{1.73}$). The ratio between the number of species per locality in shale and limestone for Group A was .765 ($\frac{2.15}{2.81}$), a number differing so greatly from the ratios for Groups B and C that the ratios between the number of species per locality in sandstone and limestone was computed for Groups A and B, giving .985 ($\frac{2.77}{2.81}$) in the former and .982 ($\frac{1.70}{1.73}$) in the latter case. For Group C this computation was of course impossible, owing to the absence of collections from sandstone. In view of the multiplicity of the problems involved and the entire lack of interrelation between the groups into which the localities were divided, the ratios afford fairly clear evidence of the accuracy of all of the figures except 2.15, the number of species per locality in shale for Group A, and would seem to indicate that the number of species per locality is smaller in shale than in sandstone and greatest in limestone.

The accordance of the results is all the more remarkable when we remember that the following factors, if they were not more or less compensatory, might easily have vitiated the results: (1) Errors in the identification of the sediment due to the presence in the collections of gradational types whose classification was of necessity somewhat arbitrary; beds neither predominantly arenaceous or calcareous, for example, which might on second examination be referred differently; (2) errors in the determination of the true nature of the inclosing sediment because of local variations in the matrix immediately surrounding the fossil; and (3) errors in the identification of the species themselves. Most of the determinations of sediment were made by examination of the hand specimens on which the species are preserved, and in no case have these original results been verified or changed. For this reason the one sandstone representative of the genus *Huenella* may either be incorrectly assigned to that genus or may occur in a sandstone calcareous enough to justify its transfer to the limestone column. On the other hand, both of these identifications may be correct and the genus may occur in both types of sediment.

The results do not necessarily prove that a species is to be considered as generally confined to one type of sediment; it may have been collected from shale only, for example, when it may also occur in sediments of entirely different character, but of identical age, in which it has not yet been discovered. Neither can the single fact that two beds of unlike lithologic characters bear different faunas be advanced as an indisputable argument against their contemporaneity. Certain it is that modern brachiopods appear to be able to exist at widely differing depths without observable modification in structure, and we know of apparently identical fossil forms which have preserved their individuality through lateral as well as vertical changes in the character of the inclosing sediment. We should be justified, however, in saying that the evidence at hand for the Cambrian and related Ordovician Brachiopoda points largely to a more or less positive influence of the character of the sea-bottom on both the nature and the number of the inhabiting species.

SUMMARY

A careful study of the known Cambrian and Lower Ordovician brachiopod localities considered in this paper shows (*a*) that the 47 genera, 16 subgenera, 519 species, and 60 varieties represent 1,460 localities in 16 countries and 5 continents; (*b*) that from about 72 per cent of the localities represented in the United States National Museum brachiopods have been identified; (*c*) that, dividing the sediments into three groups (shale, sandstone, and limestone), 41 per cent of the genera and subgenera and 74 per cent of the species and varieties appear to have been identified from but one type of sediment;⁹ (*d*) that of the 26 genera and subgenera which appear to be confined to one type of sediment only 14 (or 22 per cent of the total number of known genera) have been identified from more than one faunule, but that of this number ten (or 71 per cent) are confined to sandstone; (*e*) that 44 per cent of the species occurring in more than one type of sediment have been identified from more than one of the three main divisions of the Cambrian; (*f*) that of the species common to differing types of sediment, 63 per cent have been collected from more than one State or similar artificial unit, and that of this number 55 per cent are also common to separable geologic provinces; (*g*) that the species occurring more than once in the same section largely (45 out of 70) accommodate themselves to vertical changes in the character of their inclosing sediment, though an appreciable number (14)

⁹ These figures (41 and 74) become reduced to 22 and 35 per cent respectively by the elimination of (*a*) genera represented by single species in single faunules and (*b*) species represented by single localities.

frequent both facies of an interbedded series; (*h*) that of the 45 species just mentioned the number occupying positions in the stratigraphic sequence where the gradation upward is from the more elastic to the less is from two to five times that of species showing the reverse progression; and (*i*) that after dividing the 1,460 localities into three entirely distinct and unrelated groups there are obtained for each of the groups and for each of the types of sediment average figures which bear striking mathematical evidence of the reliability of their indication that while the number of species per locality is remarkably uniform it is smaller in shale than in sandstone and greatest in limestone.

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CONTENTS

	Pages
Diamond Hill-Cumberland District in Rhode Island- etts. By Charles H. Warren and Sidney Powers -	435-476
thesis of Climatic Changes. By Ellsworth Hunting- - - - - -	477-590
Lavas. By J. Volney Lewis - - - - -	591-654
nposition of Clastic Sediments. By Johan A. Udden.	655-744
s and the Oolitic Texture in Rocks. By Thomas C. - - - - -	745-780
ne 25 - - - - -	781-802
ents, etcetera, of Volume 25 - - - - -	i-xviii

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GEOLOGY OF THE DIAMOND HILL-CUMBERLAND DISTRICT
IN RHODE ISLAND-MASSACHUSETTS¹

BY CHARLES H. WARREN AND SIDNEY POWERS

(Presented before the Society December 31, 1913)

CONTENTS

	Page
Introduction.....	436
Previous work.....	438
Location and topography.....	438
Summary table of rock formations.....	439
Pre-Cambrian rocks: Blackstone series.....	440
Nomenclature.....	440
Structure.....	441
Cumberland quartzite.....	441
Ashton schists.....	442
Smithfield limestone.....	443
Age relations.....	443
Cambrian rocks.....	445
Pennsylvanian rocks.....	446
Subdivisions.....	446
Narragansett series.....	447
Bellingham series.....	448
Igneous rocks.....	449
Pre-Cambrian.....	449
Gabbro.....	449
Cumberlandite.....	450
Serpentine veins.....	451
Labradorite porphyry dikes.....	452
Middle Devonian.....	452
Quartz diorite.....	452
Milford granite.....	454
Joes Rock granite, porphyry, and felsite.....	456
Grants Mills granite.....	458
Comparison of the biotite granites.....	459
Lower Pennsylvanian.....	461
Diamond Hill felsite.....	461
Wamsutta volcanoes.....	462
Middle Pennsylvanian.....	463

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	Page
Riebeckite-ægirite granite.....	463
Quantitative studies.....	465
Inclusions.....	467
Riebeckite-bearing granite porphyry.....	467
Diamond Hill quartz deposits.....	471
Sheldonville quartz vein.....	473
Post-Permian diabase dikes.....	474
Summary.....	475

INTRODUCTION

The area which it is the purpose of this paper to describe is of interest to petrologists because of the occurrence within its borders of the rare ultrabasic rock cumberlandite, of a considerable mass of riebeckite granite and associated porphyries, and of the remarkable quartz deposit known locally as Diamond Hill. As will appear beyond, all three of these formations, as well as the general geology of the region, have been made the subject of more or less study by workers in this field. A desire to ascertain more fully the relations and characteristics of the riebeckite rocks was the particular motive that led the present writers to take up the study of the region, and while this phase of the investigation was the main object, it has been thought well to extend somewhat the scope of the paper, so as to include a description of the surrounding formations for a few miles on all sides.

Besides giving the relations of the riebeckite granite, it is hoped that the present paper will contribute something to the knowledge of the biotite granites, whose identity or non-identity are the subject of so much dispute. The riebeckite rocks near Cumberland Hill mark, so far as is known, the southernmost extension of rocks characterized by the essential minerals, microcline-micropertthite and alkali hornblendes or pyroxenes, or both, which are so prominent a feature of the petrology of the eastern part of Massachusetts and which reach their most important development in the Quincy-Blue Hills area and from Salem and Marblehead northward to the extremity of the Cape Ann Peninsula.

The accompanying geologic map, based on a large amount of detailed work, has been prepared to give as accurate an idea as possible of the distribution of the various rock types. The boundaries are in part hypothetical, particularly for that part of the map which lies in Massachusetts and in the vicinity of the Blackstone River, where outcrops near contacts are rare. In places where bedrock is covered by drift so efficiently as to render the mapping of the former impossible, a blank space has been left

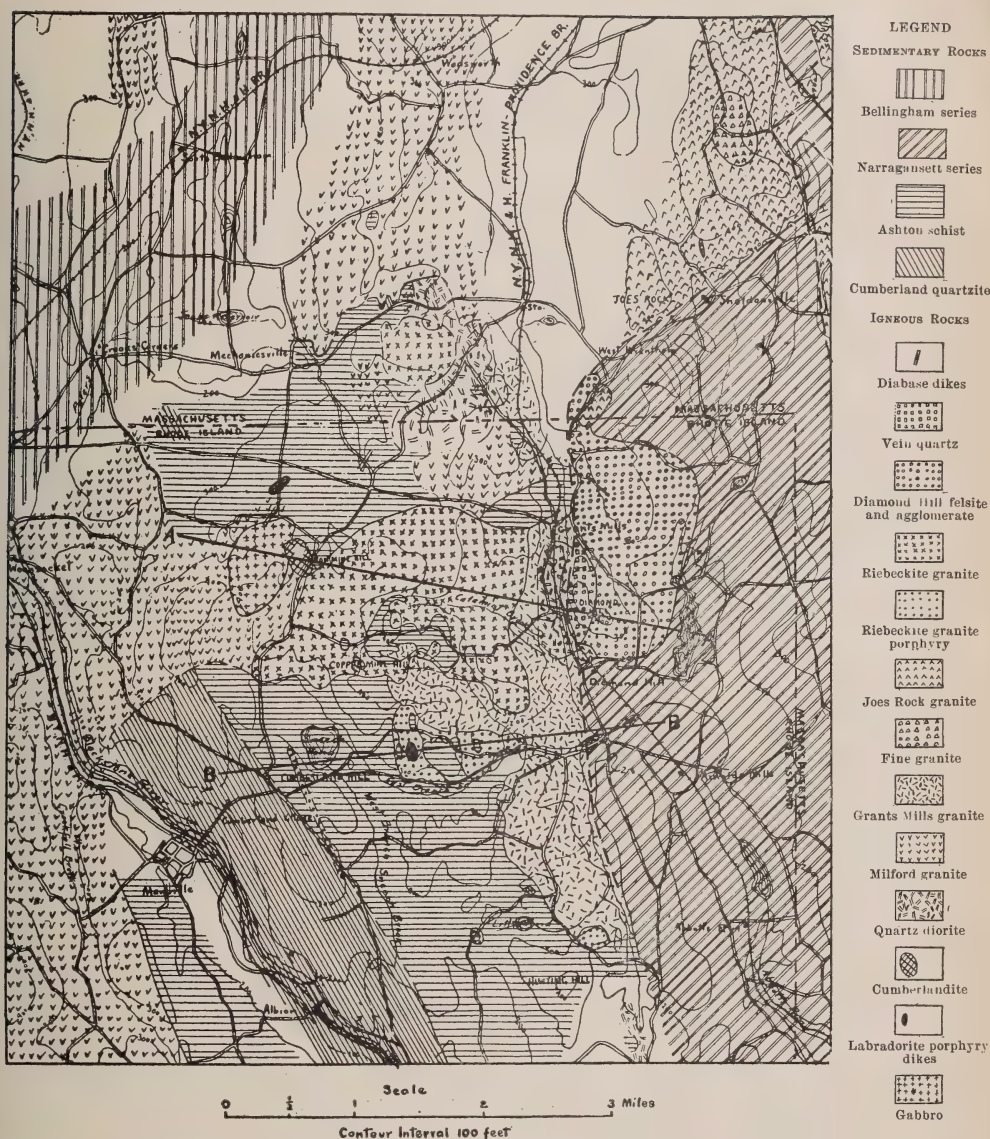


FIGURE 1.—Map of Diamond Hill-Cumberland Hill Region

on the map. It may be noted that the paucity of outcrops at many critical points seems to be a characteristic of the area and makes it difficult or impossible to settle certain questions of considerable interest with the certainty that is desirable. A comparison of this map with that pub-

lished by Emerson and Perry,² where the two maps overlap, will show certain points of difference. However, the very considerable care with which the writers have gone over the area in question inspires them with considerable confidence as to the accuracy of the map herewith presented.

PREVIOUS WORK

The first work on the general region of which the present limited area is a part was done by Dr. C. T. Jackson and was recorded in his report on the "Geology and Agriculture of the State of Rhode Island," published in 1840. The next work of importance was by Shaler, Woodworth, and Foerste in their monograph³ on the "Geology of the Narragansett Basin." Professor Woodworth in his section of the monograph describes some of the igneous and sedimentary rocks occurring in the region now under consideration. B. K. Emerson and J. H. Perry, in the bulletin previously referred to, discuss the green schists and associated rocks in the region south of Iron Mine Hill. B. L. Johnson⁴ has described briefly the geology of Iron Mine Hill, and one of the authors has described in considerable detail the petrography of the cumberlandite and the closely associated gabbro⁵ from the same locality.

LOCATION AND TOPOGRAPHY

The Diamond Hill-Cumberland Hill area is located at the northeastern corner of the State of Rhode Island and in the adjoining part of Massachusetts. The western edge of the district is a mile east of Woonsocket, Rhode Island.

In the center of the area is Copper Mine Hill, on the east is Diamond Hill, and on the west is Iron Mine Hill. All three hills rise to an elevation of over 400 feet above sealevel, or about 300 feet above the two streams in the region—the Blackstone River on the west and Abbotts Run on the east. On the north the upland topography continues beyond the boundary of the map.

The relation of topography to bedrock geology is clearly shown. The three hills mentioned above consist of igneous rock, as does the ridge to the north. On the northwest and southeast are rather flat, low regions underlain by the softest and most easily eroded rock in the region—Carboniferous sediments. The meandering brooks in these low regions are

² Bull. U. S. Geol. Survey No. 311.

³ Monograph U. S. Geol. Survey No. 33.

⁴ Am. Jour. Sci., vol. 25, 1908, pp. 1-12.

⁵ Am. Jour. Sci., vol. 25, 1908, pp. 12-38.

of postglacial development. The Blackstone River flows through granite and hard quartzite, but the course of this river was determined in preglacial times by the strike of the bedding and of the schistosity of the rocks. Both the bedding and schistosity in this locality trend in a north-west-southeast direction.

The effect of Pleistocene glaciation has been to modify the topography, scouring off the hills and filling the valleys. Prof. N. S. Shaler estimated that at least 200 feet of cumberlandite had been removed from the top of Iron Mine Hill by the various glacial advances. He traced the boulder train from this hill for 60 miles.⁶

In the region west of the Blackstone River and in the district north of Grants Mills the bedrock is quite effectually concealed under glacial deposits consisting largely of stratified gravels; also the Carboniferous sediments are covered with glacial material, making it impossible to trace out the boundary of the Bellingham series.

Postglacial erosion has removed less than an inch from the softer rocks of the region and weathering has in general penetrated the granites for a distance of only a few inches. Glacial striæ have in general been removed from the rocks. In the pre-Cambrian conglomerates the glacially polished hard pebbles stand out in relief from the softer matrix.

SUMMARY TABLE OF ROCK FORMATIONS

Following is a concise summary of the formations in the area under consideration:

Sedimentary rocks.

Pre-Cambrian.

Cumberland quartzite, including interbedded schist.

Ashton schist, including chlorite-epidote schist, hornblende schist, blue quartz schist, and interbedded Smithfield limestone.

Lower Cambrian.

Limestone fossiliferous boulders, red and light yellow shale, and some fragment of quartzite.

Pennsylvanian.

Narragansett series.

Wamsutta red beds, including conglomerates, shales, and sandstones of red color.

Pawtucket formation, including some conglomerates, but principally sandstones and shales, often of reddish-green color.

Bellingham series.

Green schists.

Conglomerates, greatly sheared.

⁶ Bull. Mus. Comp. Zool. Harvard Univ. No. 16, 1893, pp. 185-225.

Igneous rocks.

Pre-Cambrian.

Gabbro.

Cumberlandite.

Labradorite porphyry dikes.

Middle Devonian.

Quartz diorite.

Milford granite.

Grants Mills granite, including fine granite.

Joes Rock granite, including quartz porphyry, feldspar porphyry, fine granite, and felsite.

Lower Pennsylvanian.

Diamond Hill felsite.

Middle Pennsylvanian.

Riebeckite-agirite granite.

Riebeckite granite porphyry.

Diamond Hill quartz veins.

Sheldonville quartz vein.

Post-Permian.

Diabase dikes.

PRE-CAMBRIAN ROCKS: BLACKSTONE SERIES

NOMENCLATURE

In the region southeast of Woonsocket and west of Providence there occur two large areas and several small areas of highly metamorphosed rocks referred by Woodworth⁷ to the pre-Cambrian and named the Blackstone series. They consist of green schists, quartzites, and some limestones. These metamorphic rocks occur as huge isolated blocks in granite. On one side only they are in contact with the Carboniferous sediments, and this contact is either a fault or an unconformity.

The largest of the "blocks" extends from Lonsdale, northwest of Pawtucket, to Copper Mine Hill. The northern half of it is shown in the accompanying map. The other occurrences of the Blackstone series are south of the area here mapped.

Woodworth divided the rocks of the series into three formations—the Cumberland quartzites, the Ashton schists, and Smithfield limestones. He did not map these formations, but used the names as locality terms.

Emerson and Perry⁸ separated the series into four formations, dividing the schists into two parts. They named the quartzite from a similar rock at Westboro, Massachusetts. These subdivisions, with their relative positions, are as follows:

⁷ Monograph U. S. Geol. Survey No. 33, p. 104.

⁸ Bull. U. S. Geol. Survey No. 311, p. 10.

"1. A central band of phyllite and fine-grained micaceous quartz schist, the Albion schist member.

"2. Two flanking bands of granular massive quartzite, the Grafton quartzite.

"3. Two broad exterior bands of green schists and amphibolite, the Marlboro formation.

"4. Thick beds of crystalline limestone, the Smithfield limestone, with intercalated soapstones and serpentine."

It has been found that there is no continuous central band of schist as mapped by Emerson and Perry. Instead, there are only occasional outcrops of green schist in a mass of quartzite which is well exposed along the east side of the Blackstone River in rocky ledges. The schist is apparently interbedded in the quartzite. The line of the new Grand Trunk Railway extends along the east side of the river to a point just south of Albion, and the excavations have exposed several contacts of the quartzite and schist. Northwest of Albion, along the New York, New Haven and Hartford Railroad, there are large outcrops of both quartzite and schist. Interpreting the schist in this manner, it is necessary to adopt the nomenclature proposed by Woodworth.

STRUCTURE

The structure of the Blackstone series is very obscure on account of the large amount of alteration and metamorphism to which these rocks have been subjected. The series has in general a northwest-southeast strike and a prevailing dip to the east, usually at a high angle. The central band of quartzite and interbedded schist is older than the Ashton schists. The evidence of this is found in the pebbles of quartzite found in the conglomeratic facies of the Ashton schists. The previous workers in the region have held a similar opinion as to the relative ages of the two formations. The quartzites appear to form a closed anticline, with the Ashton schist on either side. There are several isolated patches of quartzite on the east, indicating that quartzite underlies the Ashton schists in this locality. It is difficult to account for so broad a band of schist—originally 4 miles or more—on the east, but this is not a valid reason for considering that the series was originally more than two miles in thickness.

CUMBERLAND QUARTZITE

The Cumberland quartzite, as here defined, consists of quartzite and interbedded schist. As noted above, the schist can not be distinguished in mapping from the quartzite. The latter is a fine-grained, massive, quite pure white rock, usually stained light yellow by the introduction of iron oxide. When it is impure, thin plates of muscovite have been developed along planes of shearing. By a further increase of mica the rock becomes a schist.

The massive quartzite is exposed near Albion, on the east side of the Blackstone River, in a long ridge extending parallel to the river. The cuts of the Grand Trunk Railway expose a section from this point to Manville, on the east side of the river. Occasionally bands of greenish gray phyllite occur in the quartzite and furnish a guide to the bedding.

The quartzite is practically confined to a broad belt along the Blackstone River. A small amount of the same rock occurs northwest of Iron Mine Hill, at the State line. There are a number of outcrops of quartzite at this point, with Ashton schists on the east. North of Little Pond are several xenoliths of quartzite of considerable size in Grants Mills granite.

The phyllite is exposed southeast of Manville, on the east bank of the river, and also in some railroad cuts on the west bank. The rock is usually dark gray in color and thin-bedded, showing abundant mica. The phyllite consists of minute grains of quartz, flakes of muscovite and biotite, and crystals of magnetite. Epidote does not appear to be present in the fresh rock.

ASHTON SCHISTS

The most widespread rock of the entire area is a green to almost black schist which stretches far east of the Blackstone River, inclusions of it being found in the granite of Joes Rock. All the igneous rocks of the area have apparently been intruded partly into this schist and the older Cumberland quartzite, which together formed the "Grundgebirge" of the region.

The Ashton schist is in the main a greatly sheared and altered chloritic rock, usually thin-bedded and green in color, with abundant epidote developed as nodules and as ramifying veins. Sometimes, however, it is a hornblende schist, a green actinolite schist, or a massive, blackish quartz schist. West of Manville there is a micaceous blue quartz schist associated with the common green chloritic variety.

In several places the schist grades into a conglomerate. There is an exposure of the latter a short distance north of the gabbro which outcrops west of Iron Mine Hill. The conglomerate here consists of occasional pebbles of Cumberland quartzite in a green schistose matrix. The pebbles are, on an average, an inch long and well rounded. The maximum length of the pebbles is 4 inches. The beds strike north 72 degrees west and dip 45 degrees east. Another exposure of conglomerate is found on a hill one mile west of the West Wrentham station, near the contact of the riebeckite granite with the schist. The pebbles here consist largely of a granite which superficially resembles the Milford granite, but which is not now represented in the area.

The common type of schist is colored green by the abundant chlorite. Epidote occurs in the body of the rock as well as in conspicuous nodules and veins. Some of these veins are a foot in width, but most of them are less than half an inch wide. The epidotization has apparently taken place in connection with the folding of rocks in pre-Cambrian times and also in connection with later granitic intrusion. Epidote is often found covering quartzite pebbles, as if replacing quartzite. One large "augen" of feldspar has been found in the schist.

Under the microscope the normal schist is seen to consist of chlorite, sericite, quartz, magnetite, biotite, and muscovite. The rock is very fine-grained.

Hornblende schist is found in the vicinity of Sneece Pond and also a mile north of Little Pond. It shows hornblende crystals half an inch in length by a quarter of an inch in width. The origin of the rock is possibly igneous.

The blue quartz schist west of Manville occurs at the contact of the Ashton schist with the Milford granite. The quartz crystals are rather conspicuous in a matrix of greenish mica and fine quartz grains. In thin-section the rock consists of knots of brecciated quartz, abundant biotite, with smaller amounts of plagioclase, epidote, hornblende, chlorite, and a little magnetite. In all probability this rock was of igneous origin.

SMITHFIELD LIMESTONE

Occasional patches of interbedded limestones occur in the Ashton schist. Several beds of this Smithfield limestone occur 3 miles south of Albion, at Lime Rock. Limestone was quarried on Copper Mine Hill in the latter part of the eighteenth century for the copper it contained, and one quarry is still visible about one-half mile east of Sneece Pond, north of the road to Diamond Hill.

Dr. C. T. Jackson in 1840⁹ reported a bed of limestone near Sneece Pond 6 to 10 feet thick, with a strike of north 25 degrees west and a dip of 35 degrees east and overlain by granite. He states that the limestone contained chalcopyrite, tremolite, asbestos, and actinolite. The origin of this limestone may be a large calcite vein in the Ashton schist, for several smaller calcite veins occur in the vicinity.

AGE RELATIONS

Previous to the work of Emerson and Perry, the Blackstone series were considered pre-Cambrian by C. T. Jackson, Crosby, Shaler, and

⁹ Report on the Geological and Agricultural Survey of the State of Rhode Island.

Woodworth.¹⁰ The latter bases his opinion as to their age on the relative degree of metamorphism between this series and the Lower Cambrian fossiliferous series of Hoppin Hill, North Attleboro. He says:

"The *Olenellus* fauna occurs in *little-altered*, red calcareous shales and slates at North Attleboro in close proximity to granite. Four miles west of this inlier of the Carboniferous area occur the sediments involved in the Blackstone series complex. These strata are *highly altered* sediments, now hornblendic and chloritic schists, mainly of a green color, altered sandstones or quartzites, and crystalline limestones. . . . The criterion appealed to in this case is embodied in the statement that where two sets of rocks coexist in the same dynamic field, that group which has undergone movement more than the other is the older. If this view is maintained, this series of rocks falls into the pre-Cambrian."

As no fossils have been found in these rocks, the only criteria for the determination of age are the lithological resemblance of the series to the rocks in near-by fossiliferous horizons and the relative degree of metamorphism. These will be discussed in this order.

Any determination of age on purely lithologic evidence is of doubtful value. In the district under consideration four fossiliferous Cambrian localities have been found.¹¹ Three of these are near Hoppin Hill, already referred to, and the other is at a place about two miles north of the town of Diamond Hill, within a few hundred feet of the Massachusetts-Rhode Island line. The Cambrian

"consists chiefly of reddish and greenish shales and slates with whitish and reddish layers and nodules of limestone. Sandstone beds are known at almost all exposures, but form only a very unimportant element of the *Olenellus* Cambrian, so far as this horizon has been definitely recognized."¹²

Emerson and Perry say of the Blackstone series:

"The highly ferruginous and highly calcareous green schists must have been derived from rocks exactly like the red calcareous shales of the 'Attleboro series,' and the quartzites from rocks closely like the sandstones of the Brain-tree Cambrian" (page 34).

On the other hand, there is apparently no reason why the rocks of the "Attleboro series" could not have been derived from the Blackstone series, or why both could not have been derived from similar rocks. They then attempt to compare with the Blackstone series the Cambrian quartz-

¹⁰ C. T. Jackson: Op. cit.

W. O. Crosby: Geology of Eastern Massachusetts, 1880, p. 128.

Shaler: Bull. Mus. Comp. Zool. Harvard College, vol. 16, 1888, p. 15.

Woodworth: Monograph U. S. Geol. Survey No. 33, p. 105.

¹¹ A. F. Foerste: Monograph U. S. Geol. Survey No. 33, pp. 386-393.

¹² A. F. Foerste: Op. cit., p. 393.

ites of Berkshire, which are obviously too far away to enter into the question. They also compare the former with pre-Carboniferous schist at the southern end of Conanicut Island, and with other similar unfossiliferous rocks near Little Compton and Newport, whose age is unknown. There is nothing conclusive about any of these instances. Therefore the only criterion remaining is that of relative metamorphism.

In southeastern New England only two periods of mountain-building have been recognized, the pre-Cambrian and Permian. The effects of the latter are apparent throughout the Narragansett Basin and in other rocks in the vicinity. The metamorphism accompanying this orogenic movement has been more intense in the southern part of the Narragansett Basin than in the northern part, but no sharp line can be drawn, as Woodworth represented, between the metamorphosed and the unmetamorphosed portions.¹³

In the area considered in this article the metamorphism has affected most severely the part west of a north-south line connecting Sneece Pond with Iron Mine Hill. Thus the granite porphyry on Cumberland Hill, the riebeckite granite at its western edge, the cumberlandite and gabbro near Iron Mine Hill, and the Milford granite and Bellingham series west and northwest of the cumberlandite are all more or less sheared, often with a development of a gneissic or schistose structure. The Milford granite and Bellingham series have been sheared the most, as will be discussed later. The main mass of the riebeckite granite and biotite granite east of it show less metamorphism. The Blackstone series, occurring to the north and to the south of the riebeckite granite, and the large body of green schist surrounded by the granite show the effects of an intense and ancient metamorphism accompanied by alteration producing chlorite and epidote in all of the green schists. It is clear that this metamorphism could not have taken place in the Permian revolution, or the granite would be affected near the schist. Moreover, a half mile north of the last outcrop of this schist north of Grants Mills occur Cambrian fossiliferous limestone boulders which Foerste considers to be almost in place.¹⁴ This limestone is not metamorphosed.

On the strength of all this evidence, it seems fairly certain that the Blackstone series are pre-Cambrian and were metamorphosed in pre-Cambrian times.

CAMBRIAN ROCKS

In his work on the Narragansett Basin, Foerste found some boulders

¹³ F. H. Lahee: *Am. Jour. Sci.*, 4th ser., vol. 33, 1912, p. 249 ff.

¹⁴ *Op. cit.*, p. 393.

of fossiliferous Lower Cambrian rocks on the Joes Rock granite hill south of West Wrentham, a short distance north of the State line.

"After following the southern margin of the granite hill eastward along the base of the hill for a distance of several hundred feet, a change in direction of the border toward the northeast takes place. Here a number of red limestone boulders are found on the hillside. Toward the brow of the hill there is a fair exposure of red shales dipping at a high angle westward and striking east of north. West of these, quartzitic beds probably occur, as is shown by fragments in the soil and on the hillside.

"The loose boulders on the hillside evidently are almost *in situ* and contain *Hyolithes princeps*? and *Hyolithellus micans*?. From the top of this part of the hill it is a distance of about 100 feet to the border of the granite mass forming the main body of the hill. Along the brow of the hill westward the granite is purplish or brownish rock, which may possibly be fragments of *Olenellus* Cambrian shale hardened by metamorphism."¹⁵

The purplish rock referred to last was found on the hill, included in Joes Rock granite, as described. The inclusion is about 3 feet long, but only a few inches wide. Under the microscope the rock is seen to be quite different from the pre-Cambrian and Carboniferous schists. It consists largely of hematite and magnetite with some quartz and muscovite. With the purple slate was found one of light yellowish color. The fossiliferous limestone boulders were not found.

PENNSYLVANIAN ROCKS

SUBDIVISIONS

The Carboniferous rocks of the area considered in this paper are divided into two series, now separated by about 4 miles of other rocks. In the eastern and southeastern part of the area the sediments of the Narragansett Basin occur. For convenience they will be called the Narragansett series. In the northwestern part of the area there is another sedimentary series which is more fully exposed near the town of Bellingham; it will therefore be called the Bellingham series. The relation of these two series is at present unknown, but it is probable that they were formerly connected with each other and with the Carboniferous sediments of the Boston Basin, the Norfolk Basin, and the newly discovered South Framingham Basin. The most apparent difference between the Narragansett series and the Bellingham series is in the color of the sediments—the former are red and the latter are dark green. There is also a great difference in the amount of metamorphism to which these sediments have been subjected. The Bellingham series has been intensely

¹⁵ Monograph U. S. Geol. Survey No. 33, p. 393.

metamorphosed, whereas the Narragansett series has been folded with but little shearing.

NARRAGANSETT SERIES

The northeastern edge of the Narragansett Basin is in the area south of Sheldonville, Massachusetts, and east of Diamond Hill, Rhode Island, at the northeastern edge of the area mapped in the southern end of the Norfolk Basin. The Narragansett series consists, according to Woodworth, of four formations:

Dighton group,
Pawtucket formation,¹⁶
Wamsutta red beds,
Pondville arkoses,

arranged in the order of their stratigraphic position.

In the area mapped in this paper the Pawtucket and Wamsutta formations are exposed, the former along a narrow strip south of the Diamond Hill felsite and the latter on the east of this strip and of the Diamond Hill felsite.¹⁷

The structure of the Narragansett series in a section from Arnolds Mills westward is monoclinal, the beds dipping southwest at an angle of about 30 degrees and striking north 75 degrees west. They are cut off by the north-south fault running west of Diamond Hill. Near Sheldonville the strike is nearly parallel to the northeast-southwest fault and the dip is about 40 degrees north.

The existence of these faults is proven by the dips of the strata near them. The downthrow has apparently been on the side of the Narragansett series. The north-south fault past Diamond Hill was mapped by Woodworth. He also drew a north-south fault east of Sheldonville which is shown on the map accompanying this paper. The steep cliff of Joes Rock granite northeast of Sheldonville, and on this fault line, appears to substantiate the existence of the fault.

The Wamsutta red beds consist of red conglomerates, shales, and sandstones. The rocks have been tilted and compressed, as is shown by some of the conglomerates in which the pebbles have been dented or flattened by each other. Near the reservoir east of Diamond Hill there are numerous exposures of moderately coarse conglomerates and some interbedded red shales. The pebbles in the conglomerate vary in size to about 4 inches in length, but on the average they are one inch in length. They

¹⁶ The term Pawtucket formation is introduced in place of the "Coal Measures" of Woodworth in order to avoid confusion with the Coal Measures of other localities.

¹⁷ Monograph U. S. Geol. Survey No. 33, plate 17.

consist of quartzite, felsite (probably Joes Rock type), and fine and coarse granite of the biotite type. Half a mile south of West Wrentham the conglomerate pebbles consist almost wholly of Joes Rock felsite. At Arnolds Mills, near the stream called Abbotts Run, is an exposure of coarse conglomerate lying above fine reddish conglomerate. The former consists largely of pebbles of Hoppin Hill granite exposed just east of the area mapped, some of which are 10 inches long and 6 inches in diameter; also there are quartzite, vein quartz, greenish schist, Joes Rock felsite and quartz porphyry, and red sandstone pebbles of an average length of 4 or 5 inches: all are well rounded.

Along the road through Sheldonville there are several exposures of fine conglomerates, red shales, purple fine-grained sandstones, and red sandstones. These sediments are much finer-grained than those farther to the south. In an outcrop just north of the Sheldonville road, at the western end of the village, there is a cast of a Carboniferous tree-trunk 8 inches wide and $1\frac{1}{2}$ feet long.

The Pawtucket formation outcrops just south of the area shown on the map. It consists largely of sandstones and shales with some conglomerates. In one outcrop 10 feet in width nine alternate bands of sandstones and shales were exposed, the former varying in composition from an arkose to a fine quartz conglomerate. One coarse conglomerate was found $1\frac{1}{2}$ miles southeast of Hunting Hill in which some of the pebbles are 16 inches long. The prevailing strike of these beds is north 38 degrees east and the dip is 70 degrees south.

The age of the Narragansett series has been considered to be Pottsville-Allegheny (Pennsylvanian) because of the evidence furnished by plant remains. Besides these plant impressions, insect remains and a number of impressions of amphibian footprints have been found. Recently Mr. W. P. Haynes¹⁸ has found impressions of the carapaces of the bivalve crustacea *Estheria* sp. and *Leaia tricarinata*, M. & W., associated with the leaves of Cordaites and Calamites in the Pawtucket formation at Central Falls (5 miles southeast of Arnolds Mills). These fossils indicate a Conemaugh age, but are not good horizon markers.

BELLINGHAM SERIES

In the northwestern part of the area shown on the accompanying map a series of lustrous green schists and sheared conglomerates are exposed in a few outcrops. These rocks occur in greater abundance north of this area, in Bellingham, where there are some amygdaloids.¹⁹ This series

¹⁸ W. P. Haynes: Science, n. s., vol. xxxvii, 1913, pp. 191-192.

¹⁹ This information was kindly furnished by Mr. Laurence La Forge, of Washington, D. C.

extends southward through Woonsocket, as noted by Emerson and Perry. The conglomerates of the Bellingham series in Woonsocket are of very coarse white quartzite pebbles "mashed to rods and plates 12 to 14 inches long."²⁰ A similar conglomerate is exposed near the town of Crooks Corners (one mile west of Mechanicsville). Here the conglomerate consists of quartzite and Milford granite pebbles varying in length from an inch to a foot, all greatly sheared and mashed, the elongation of the pebbles being in a north-south direction. Pebbles 1 foot in length have a diameter of 3 inches. They are cemented by a light green paste. Elsewhere, as west of Crooks Corners, the green conglomerate is exposed in contact with schist. Often films of biotite have been developed along the shearing planes and on the sides of the platelike pebbles. The latter consist principally of white quartzite and green schist derived from the Blackstone series near by. In some of the sheared material the pebbles are one-fourth of an inch thick and 2 inches long or one-third of an inch thick and 3 inches long.

The schist of the Bellingham series is dark green, massive, and fine grained. It is exposed in two railroad cuts, one a mile west of Wadsworth and the other west of Crooks Corners, at the margin of the Franklin sheet. In thin-sections it is seen to consist of muscovite, quartz, chlorite, and zoisite, with some magnetite.

The Bellingham green schist can be distinguished from the green schists of the Blackstone series by its freshness, lack of alteration, and absence of epidote nodules. It is also more massive than the Ashton schists. Its relation to the latter must be an unconformity, but outcrops are so scarce in this drift-covered area that the contact of the two series can not be accurately drawn.

The age of the Bellingham series is supposed to be the same as that of the Narragansett series. The character of the rock with its associated amygdaloids places it unquestionably in the Carboniferous.

IGNEOUS ROCKS

PRE-CAMBRIAN

Gabbro.—West of Iron Mine Hill is a mass of highly altered gabbro. It is surrounded by pre-Cambrian schist and Milford granite. Several inclusions of the gabbro have been found in the cumberlandite of Iron Mine Hill. A mile west of the West Wrentham railroad station, near the contact of the Milford granite and the quartz diorite, is some pre-

²⁰ Emerson and Perry: *Op. cit.*, p. 38.

Cambrian schist and a highly altered and sheared rock which appears to have originally been a gabbro. The latter is intrusive into the schist.

This gabbro²¹ is exposed in a relatively fresh condition only in cuts along a deserted railroad running from Iron Mine Hill to the Woonsocket road, a mile to the west. From this locality it may be traced into a greenish white schist, the extremely sheared and altered phase of the rock.

The fresh gabbro is a medium to coarse-grained, greenish to brownish rock consisting originally of plagioclase, augite, ilmenite, magnetite, and apatite. In the least altered phase the plagioclase is a labradorite of about the composition Ab_1An_1 , occurring in tabular crystals. These are comparatively fresh, but are colored brownish by a pigment present within the crystals. The augite has been largely altered to secondary hornblende accompanied by more or less biotite. In this alteration have also been involved the large ilmenite grains originally closely associated with the augite, and the adjacent labradorite crystals. Further alteration, accompanied by shearing, has saussuritized the feldspar, altered the hornblende and biotite to chlorite and epidote or zoisite, and scattered these products generally through the rock. The remaining ilmenite formed leucoxene. The original texture of the gabbro is thus largely destroyed. Further metamorphism has reduced the rock to a compact green schist in which almost all traces of the original rock structure has been lost. For further details of the chemical composition and metamorphism, etcetera, of this rock the paper above referred to may be consulted.

The age of the intrusion of the gabbro is placed in the pre-Cambrian, in part by reason of the evidence found west of West Wrentham, as noted above, and in part by reason of the fact that this gabbro is probably a southwestward extension of a band 2 miles wide of very similar rock extending from near Sheldonville through Sharon to Canton Junction, a distance of 14 miles. The gabbro east of Sheldonville is cut by biotite granite and is, therefore, older than the granite.²²

Cumberlandite.—The cumberlandite is perhaps the most interesting rock petrologically which is found in the area, but as it has been fully described by one of the writers a brief summary will suffice here.²³ The rather prominent rounded knob known as "Iron Mine Hill" consists entirely of this rock. It is exposed as a roughly elliptical, dikelike boss

²¹ See paper by C. H. Warren in *Am. Jour. Sci.*, vol. 26, 1908, pp. 469-477.

²² This rock has been studied by Mr. W. P. Haynes and also by Mr. G. E. Goodspeed, Jr., whose field reports were consulted by the writers.

²³ *Op. cit.*

having a length of at least 1,200 feet and a width of about 600 feet. It cuts the pre-Cambrian schist on the east and the gabbro on the west. The northern and southern extensions are obscured by drift. The greater part of the mass, as at present exposed, consists of altered phases. The extreme phase is greenish black in color and consists of a dense, fine-grained mass of ilmenite, magnetite, serpentine, chlorite, and actinolite. Its otherwise almost dense texture is relieved by irregular dull green spots of serpentine and chlorite which mark the positions of original labradorite phenocrysts. In the less highly altered phases a considerable part of the original olivine remains. The original rock, exposed on the western central side of the hill, consists of a fine-grained groundmass of olivine (hyalosiderite), 40 per cent, and enmeshing magnetite and ilmenite, 18 and 20 per cent respectively, crystallographically intergrown, embedding relatively large phenocrysts of labradorite occurring singly and in clusters. The feldspar constitutes about 10 per cent of the whole. In the ore matrix are about 3 per cent of dark green spinal crystals.²⁴

In narrow veins traversing the cumberlandite are found crystallizations of actinolite, clinocllore, and hortonolite.²⁵ Occasional narrow veins of fibrous, brittle serpentine also occur in a few places. Many years ago the cumberlandite, containing, as it does, 30 per cent of iron, was mined, and when mixed with hematite ores from other localities, particularly that of Cranston, Rhode Island, is said to have yielded an excellent quality of iron. It has been more recently exploited, without apparently much success, as a road metal.

The cumberlandite is known to be younger than the gabbro on the west. Further than this, there is no evidence concerning its age. It was probably intruded in later pre-Cambrian times and may be a differentiate of a pre-Cambrian magma. It may, on the other hand, be of much later date.

Serpentine veins.—In a field west of Iron Mine Hill, underlain by either granite or gabbro, probably by the former, there are several large angular boulders of dense, bluish gray serpentine which appear to be almost in place. These boulders form a mass about 5 feet in width, 10 feet in length, and 5 feet in height. Dr. C. T. Jackson in 1840 reported serpentine to occur at this locality in the form of a dike. It is probable that these boulders are in place, but that they have been blasted to make the field suitable for ploughing. The serpentine to the west of the hill

²⁴ Rounded boulders of this rock are abundant in the drift to the southward of Iron Mine Hill, and when deeply altered and covered with rust, as they usually are, they suggest very strongly a meteorite in appearance. Such boulders are, in fact, frequently mistaken for meteorites.

²⁵ C. H. Warren: Z. K. No. 19.

may be connected in origin with the alteration of the magnesium-rich cumberlandite only a short distance away.

Labradorite porphyry dikes.—Three dikes of labradorite porphyry have been found, all of which cut the Ashton schists. One of them is half a mile east of Sneece Pond, a few hundred feet south of the upper road. A second is found north of Iron Mine Hill outcropping in a north-south road. A third and narrow dike (4 inches) is noted by Johnson,²⁶ cutting the gabbro southwest of Iron Mine Hill.

At the first locality the rock is dark gray and badly weathered, and the large labradorite phenocrysts, many of which were one inch long, have now in large part disappeared, calcite being deposited in their place. A thin-section shows that the rock consists of large labradorite phenocrysts in a fine groundmass of lath-shaped labradorite, biotite, calcite, magnetite, and quartz.

In the dike north of Iron Mine Hill the rock is also dark gray in color, but is fine grained. The feldspars are about one-eighth of an inch long, and are well striated. There are several outcrops in this locality, but the contact with the Ashton schist is not exposed. The dike is cut by numerous stringers of Milford granite.

The dike east of Sneece Pond shows shearing and long weathering. The age of these dikes is post-Ashton schist, pre-Milford granite, probably late pre-Cambrian.

MIDDLE DEVONIAN

Quartz diorite.—Quartz diorite outcrops in four localities in the area mapped. The largest and most conspicuous is a mass of irregular outline beginning west of West Wrentham and extending south and southwest toward Iron Mine Hill. The boundaries of this mass are concealed by drift. Another mass is found south of Grants Mills. It outcrops in several places and appears to underlie the valley at this place. A third locality is found at the extreme southern end of the area, south of Hunting Hill. Here again lowlands and drift conceal most of the bedrock. The fourth locality is a dikelike mass only a few square feet in area, so far as can be judged from the outcrop, a half-mile north of Albion. Emerson and Perry mapped this outcrop and reported another "at the northern foot of Copper Mine Hill, on the northern border of the green schist area at the contact of the schist and the granite."²⁷ This outcrop was not found by the writers, and is therefore not mapped.

The main mass of quartz diorite is well exposed both west and south-

²⁶ Loc. cit.

²⁷ Op. cit., p. 45.

west of the West Wrentham station. The rock is dark gray in color and consists essentially of plagioclase feldspar, abundant biotite, and subordinate microcline and quartz. It is fine in grain and somewhat schistose in texture. In thin-section the plagioclase is apparently an oligoclase and is more or less automorphic in habit. Microcline, with a small amount of plagioclase intergrown with it, is distinctly subordinate to the oligoclase in amount. The quartz is crushed and is less abundant than the microcline. Biotite is abundant, mostly in the form of small flakes unevenly disseminated through the rock. Grains of iron oxide, probably titaniferous, since they are often margined with leucoxenic material, and apatite are accessory, while epidote and sericite are abundant secondary products. The last two, together with much of the biotite, are scattered through the plagioclase crystals. The rock has evidently been subjected to considerable metamorphism.

The quartz diorite of this locality is cut by many small dikes of a fine biotite granite of the Milford type, and these appear to resemble very closely the fine granite which occurs in small amount northwest of Grants Mills near the State line.

Another mass of quartz diorite outcrops prominently on the west side of the road leading from Grants Mills to Diamond Hill. A little farther west this is replaced by large ledges of the Grants Mills granite, which here seems to grade distinctly toward the diorite in mineral composition, but the contact or transition, whichever it is, between these two is unfortunately not exposed. A similar quartz diorite is found in the fields southeast of Grants Mills and also in the fields west of the quarry on Diamond Hill.

The quartz diorite from this Grants-Mills-Diamond Hill locality is a rather dark greenish gray rock, fine in grain and quite strongly sheared. It consists of heavily saussuritized oligoclase or andesine feldspar (filled with zoisite, etcetera), abundant pale green hornblende, subordinate quartz, and little or no microcline. The accessories are magnetite or ilmenite, zircon, and apatite. Some leucoxene has developed. The third locality is south of Hunting Hill, in the southern part of the field. The quartz diorite is here a dark gray-green rock of about the same grain as that west of West Wrentham. The plagioclase is andesine and is very heavily altered. Much chlorite is present, probably secondary after biotite. The southern extension of this mass has not been traced.

The Albion quartz diorite occurs apparently as a small dike cutting Cumberland quartzite. The outcrop is situated a few feet west of the railroad track, near the first quartzite outcrop north of Albion. The rock is very dark gray in color and shows hornblende crystals. In thin-

section it is seen to consist of plagioclase (probably andesine), much altered green hornblende, biotite with abundant magnetite (much of it in the hornblende), sericite, and apatite. The presence of hornblende suggests that this rock is much like that at Grants Mills.

The quartz diorites in the four localities named are apparently very closely related rocks and doubtless are identical as to origin and age. West of West Wrentham the diorite clearly cuts the pre-Cambrian Ashton schist and probably cuts also the gabbro. It is itself cut by dikes of the Milford type of granite. Although somewhat metamorphosed, as is also the Milford type of granite in the region about the diorite, neither are anywhere nearly so strongly metamorphosed as are the pre-Cambrian rocks which they cut.

At Lime Rock, 3 miles south of Albion, in the limestone quarry, Emerson and Perry found diorite pebbles in a conglomerate belonging to the Ashton schist series. Near by they found a diorite ledge with several types of rock, some of which resembled those shown in the pebbles. On this evidence they conclude that the diorite is older than the Ashton schist. There is no good reason why there may not have been diorites of pre-Ashton schist age in the area, exposed during the deposition of the schist and from which the diorite pebbles may have been derived; but the diorite found near the pebbles has not necessarily any connection with the latter. The other masses of diorite described above are quite clearly intrusive into the pre-Cambrian schist. Moreover, at a locality west of West Wrentham, as described above, pebbles of granite were found in the Ashton schist conglomerate, the pebbles resembling the Milford type of granite and its fine-grained porphyritic phases; and yet the Milford granite cuts the schist only a few hundred feet from the conglomerate outcrop. From what has been said it appears that the quartz diorite of this area is at least later than the pre-Cambrian schist, although it appears to have come into place before the granites.

Milford granite.—The Milford granite extends from its best known locality at Milford, Massachusetts, southward through the area mapped in this paper to a point below Providence, Rhode Island. The typical granite, like that from the well known quarries at Milford, Massachusetts, is a pale pinkish to cream colored rock of medium grain and distinctly gneissoid structure, marked by irregular streaks or linearly arranged patches of black mica, and to a less extent by a banded arrangement of the quartz and feldspar. The quartz is in large part "sugary." Emerson and Perry²⁸ state that the quartz is blue. So far as our ex-

²⁸ Loc., cit., p. 45.

perience goes, the quartz of the quarry granite is not characteristically blue, nor is what we should call "blue quartz" always characteristic of this granite in the present area. With a lens; and sometimes without, minute epidote grains may be seen, usually associated with the biotite, and also occasional reddish garnets.

In thin-section the rock is seen to consist of distinct crystals of albite or albite oligoclase, finely twinned after the albite, less commonly the Carlsbad law, and always more or less filled with minute grains or rods of epidotic material and scales of white mica; crystals of orthoclase or "gitter" microcline, somewhat kaolinized, in which are irregular thin lamellæ of albite, are rather sparingly present; quartz, sometimes as irregular grains, but much more generally in the form of granular mosaics; strongly pleochroic, dark greenish brown to yellow biotite in shreds and flakes, to some extent scattered, but usually strung along through the rock in streaks and elongated patches in which grains, crystals, and granular aggregates of epidote, garnet, and occasionally orthite crystals, the latter margined by epidote, are present. Some epidote and garnet occur sporadically. The feldspar crystals possess little of definite outline, although the albite sometimes indents the microcline and shows, of the two, a tendency toward more automorphic outlines. The quartz is often strung out into elongate granular streaks between the feldspars, and with the mica gives a strongly gneissoid appearance to the rock.

The characteristic thing about this granite, as of *all* the *biotite granites* of this and neighboring areas, in *contrast* to the riebeckite granites, is that there are present *distinct* crystals of sodic *plagioclase* and orthoclase or "gitter" microcline, the latter containing a little perthitically intergrown highly sodic feldspar; that there is epidote and sometimes garnet and orthite present, and that the dark constituent is biotite.

This granite in the area here described differs from the quarry granite at Milford in being in part more sheared, frequently with the development of blue quartz and also of films of muscovite along the planes of shearing. In the central and eastern parts of the area the granite is perhaps rather finer grained than the quarry granite and not so greatly sheared as to the westward.

The intensely sheared variety is well exposed in several Grand Trunk Railway cuts northeast of Woonsocket between the first and second roads south of the State line. In some places the rock has become in appearance a mica schist. The feldspar has been granulated with the quartz, but occasionally retains its pinkish color.

East of the gabbro near Iron Mine Hill the rock has a granulitic

texture-alternating bands of finely granular quartz and feldspar. Only a few feldspars retain their original size.

The Milford granite cuts the pre-Cambrian metamorphic series and is older than the riebeckite granite.

Joes Rock granite, porphyry, and felsite.—In the upland country north of Sheldonville and in a small area near the Massachusetts-Rhode Island State line just south of West Wrentham, a pink granite is exposed. In places it becomes fine and aplitic; in others it is almost felsitic, again a quartz or feldspar porphyry.

This granite is in fault contact with the Carboniferous Narragansett series in a fault running in a northeast-southwest direction just north of Sheldonville. Another fault in a north-south direction east of Sheldonville probably exists, although its extension for over a mile north of the other fault is doubtful. On the east side of this fault Joes Rock granite occurs, extending eastward through Foxboro. The exposure of granite south of West Wrentham is separated from the Narragansett series by a valley filled with glacial drift, but the sediments are known to rest unconformably on the granite.

The granite extends northward through Franklin, where it is exposed in the southern part of the village. Its extension farther north has not been traced; but, from the evidence presented below, it is probable that the granite continues northward to Dedham and merges into the Dedham granite.

On the western side of Joes Rock the valley is filled with Pleistocene deposits completely covering the bedrock. Therefore the relation of the Joes Rock granite to the Milford granite can only be inferred from their petrographical characters.

The typical Joes Rock granite has been exposed by mining operations near Sheldonville, described below. The freshest rock exposed is a coarsely crystalline feldspar quartz rock with occasional red or green spots. The pink feldspars sometimes attain a size of one-half inch square, but the average size is somewhat smaller than this. The quartz grains are about the same size, but more rounded than the feldspars. The occasional red patches consist principally of hematite and magnetite, the green patches, of chlorite.

Under the microscope the rock is seen to consist essentially of quartz, plagioclase, and microperthite, with some hematite, magnetite, sericite, chlorite, epidote, and calcite. The plagioclase is an albite or albite oligoclase and is hypidiomorphic in outline. The microperthite is slightly more abundant than the plagioclase. The microperthite consists of an intergrowth of microcline and subordinate sodic plagioclase. The quartz

shows undulatory extinctions indicating shearing and it has often been granulated. The feldspar, however, has not been greatly affected. The biotite is now largely altered, the hematite in the rock being doubtless a resulting product. The characteristic features of the rock are the small amount of femic minerals, richness in quartz, and the presence of separately crystallized sodic plagioclase. The micropertthite is more abundant and richer in plagioclase than the type Milford granite.

In the northern part of the area west of Uncas Pond the granite contains more or less light greenish feldspar as well as the pinkish feldspar. This makes the rock appear similar to the Dedham granite which occurs about 17 miles farther northeast. It is probable that these granites belong to the same batholithic injection.

The fine granite phase of the Joes Rock granite occurs on the hill south of West Wrentham on which the Cambrian pebbles have been found. It also occurs one-half mile north of Joes Rock. It is a pinkish to purplish rock with distinctly visible crystals and very little femic material. In the northeastern corner of the area, south of Uncas Pond, is a feldspar porphyry with white plagioclase feldspar phenocrysts one-sixteenth to one-fourth of an inch long in a fine-grained pink groundmass; also there is a quartz porphyry of fine grain and dark gray color within a few hundred feet of the feldspar porphyry. A felsite of dark red color outcrops on the hill one mile south of West Wrentham.

An aplitic phase of the Joes Rock granite outcrops on the road from Sheldonville to Franklin, 2 miles north of the former town. It is a very fine-grained rock, pale pink to dull red in color. Small feldspars one-sixteenth of an inch in length and a few small chlorite nodules are visible in the rock. Under the microscope it is found to consist of comparatively large plagioclase and some micropertthite crystals in a more finely crystalline mass of quartz, plagioclase, micropertthite, and a very small amount of calcite and chlorite. The plagioclase is an albite oligoclase and is free from sericite.

Contact specimens of the fine and coarse granite have been found which show that the latter retains its coarse crystal form to the sharp line of contact. The aplitic phase probably represents a marginal facies now included in the granite.

On top of Joes Rock, and near Franklin, 3 miles north of Joes Rock, are several outcrops of pre-Cambrian green schist. Another mass of Ashton schist was found near the Sheldonville quartz vein described below. These are inclusions in the granite and they indicate that the granite intruded the pre-Cambrian; also they show that the latter formerly had a much wider distribution than at present.

At Hoppin Hill, south of Attleboro and $2\frac{1}{2}$ miles southeast of Arnolds Mills, is an exposure of coarse biotite granite similar to that of Joes Rock; for convenience, it may be called the Hoppin Hill granite. The large potash feldspar crystals are the most conspicuous feature of the rock and give it something of a porphyritic habit and also its characteristic pinkish color. These feldspars may reach a length of one inch and have a thickness of one-third of an inch. The proportions of the two feldspars to the quartz is about the same as in the Joes Rock granite, but biotite or its chloritic alteration appear to be more abundant.

Thin-sections show that the feldspars are oligoclase and microcline containing the usual perthitically intergrown lamellæ of albite or oligoclase. The oligoclase and microcline micropertite are about equal in amount, and the former contains the usual minute inclusions of secondary minerals. The biotite is largely altered to chlorite. As the rock appears to have been only slightly metamorphosed, the quartz retains its original large grains with the usual allotriomorphic outlines. The general textural relations of the minerals are those found for the two previously described granites.

Grants Mills granite.—In a narrow north-south belt passing through Grants Mills a coarse biotite granite is exposed which will be called here the Grants Mills granite. There is a small quarry in this rock near the State line, at the side of the railroad running through Grants Mills. It is also well exposed on the hill west of there; other good outcrops occur along the north-south road a mile north of Hunting Hill. This granite is closely associated with the Milford granite, but the boundaries between the two can not be accurately drawn because of lack of outcrops. A fine-grained aplitic to feebly porphyritic granite appears northwest of Grants Mills cutting the other granites.

Megascopically this granite is a coarse, rather unevenly grained rock of cream, pale greenish or even pinkish color. The rather abundant larger feldspars are unstriated and attain a length of an inch or over; it is these that are sometimes greenish or pink and give color to the rock. The remainder of the rock is a rather coarse mixture of quartz and feldspar in which are quite numerous specks and platy aggregates of dark green to black biotite or chlorite. Locally the granite has been strongly sheared.

The feldspars are microcline or orthoclase, with some interwoven plagioclase and albite or albite oligoclase. In amount they are probably about equal. The plagioclase is the more automorphic of the two; it contains many minute secondary crystallizations, and in the run of sections, which do not contain the larger potash feldspar crystals, seems to predominate.

Biotite, now more or less altered to chlorite, is quite abundant. The fine granite appears to be an aplitic phase of the same granite.

Comparison of the biotite granites.—Comparing the Grants Mills and the Joes Rock granites, we find that they are substantially the same rock mineralogically and texturally, or at most they show only minor differences. There seems to be no reason why they may not belong to the same intrusion. To the northeast of the present area, at Franklin, they appear to blend, and further northward, in Sharon, they appear to merge into the Dedham granite, which, although on the whole somewhat finer in grain, possesses essentially the same mineralogical and textural features. Compared with the Milford granite, they are coarser in grain and show a greater tendency toward a porphyritic habit. The Milford granite is also, as a rule, much more strongly sheared. Aside from the tendency of the Grants Mills and the Joes Rock granites to develop larger crystals of microcline or orthoclase, they are texturally very similar to the less sheared phase of the Milford, and mineralogically they are substantially the same. So far as we can see, there is no field evidence to show that they are not of the same age and belong to one batholithic intrusion. It has not been possible to carry out a chemical study of the various types, but the microscopic evidence makes it highly improbable that there are any substantial differences chemically between them. Such differences as exist are not other than might be expected in different parts of a large batholithic intrusion such as the Milford batholith undoubtedly is, and until some positive field evidence is brought forward to show that they are of different age, we hold it best to group them all together as belonging to one period of batholithic intrusion.

We may remark here that a careful chemical study of the various types of biotite granites in eastern Massachusetts and Rhode Island is desirable. It is true that three analyses of the Milford have been made and published,²⁹ but study of them shows wide variations in several respects and leads to the suspicion that either they were not executed on suitably chosen samples or that there are errors in the analyses. At all events, they are as they stand of doubtful value from the petrographical point of view.

The age of these granites is known to be pre-Carboniferous because pebbles of them occur abundantly in the Narragansett series. On the east side of Hoppin Hill, north of the railroad track, the granite outcrops within 50 feet of the red Lower Cambrian shale. South of the railroad, 150 feet north of the road across the reservoir, are outcrops of

²⁹ These are quoted by Dale in Bull. U. S. Geol. Survey No. 358.

buff-colored sandstone or quartzite within 50 feet of the granite. This outcrop is now exposed only when the water in the adjoining reservoir is exceptionally low, but unfortunately the actual contact is even then under the groundwater level and can not, therefore, be seen. The granite is considered to be intrusive for the following reasons: (1) The strike of the Lower Cambrian fossiliferous sediments is in part at high angles to the line of outcrop of the granite; (2) the dip of the Cambrian is at a high angle, usually toward the granite; (3) the line of outcrop of the granite is irregular, apparently due to intrusion and not to faulting; (4) the Cambrian sediments nearest the granite are, in outcrops within a few hundred feet of each other, red shale, limestone, and sandstone—a relation which could not be brought about by simple faulting.³⁰

Many years ago excavations were made on the west side of Hoppin Hill which showed the granite in fault contact with the sediments. The granite has been considered to be pre-Cambrian because it was coarsely crystalline in its nearest outcrops to the Cambrian and because the latter showed no evidences of contact metamorphism. This reasoning does not seem sufficient to the writers to place the granite in the pre-Cambrian, for experience in this field generally shows that such granites sometimes remain coarse grained to within a few inches of their contact, nor do the sediments necessarily show evidences of strong metamorphism at distances as great as 50 feet from the contacts.

The only other evidence concerning the age of the granites is unsatisfactory. As discussed above, Foerste found Cambrian boulders on the Joes Rock granite hill south of West Wrentham. Furthermore, he says:

"Along the brow of the hill westward, the granite is seen to inclose long thin layers of an argillitic purplish or brownish rock, which may possibly be fragments of the Olenellus Cambrian shale hardened by metamorphism. It is impossible to determine from these inclusions whether the granite of these regions is to be considered as pre- or post-Cambrian in age. If the fragmental inclusions referred to be Olenellus Cambrian shales the granite must evidently be considered as post-Cambrian."

These inclusions of metamorphosed slate are, in our opinion, Lower Cambrian. From this and the other evidence presented in the field it seems best to date the subalkaline granites as post-Lower Cambrian. The age of the earlier series of Paleozoic biotite granites of New England must, we believe, be determined from relations found in Maine and in Nova Scotia. Near Eastport, Maine, the granites cut Silurian volcanics and pebbles of the granites are found in the Perry Basin sediments of Chemung (Upper Devonian) age. At Torbrook, Nictaux, Nova Scotia,

³⁰ For a map of a part of this locality see U. S. Geol. Survey Monograph 33, plate 37.

the biotite granites cut slates of Oriskany (Lower Devonian) age, and arkose derived from the same granites is found in the Horton series of Pocono (Lower Mississippian) age at Horton Bluff. Therefore, the age of these granites of the eastern Appalachians is inferred to be Middle Devonian.

LOWER PENNSYLVANIAN

Diamond Hill felsite.—In the region about Diamond Hill, east of the north-south fault which separates the biotite granite series from the Naragansett sedimentary series, is a large mass of felsite. Diamond Hill, as will be shown below, forms a part of the felsite area and has been extensively replaced by silica. The extent of the felsite is 2 miles in length and three-quarters of a mile in breadth. Another small occurrence of similar felsite has been found just northeast of the area here mapped.

The felsite is in general a fine-grained dense, dark green rock showing occasional phenocrysts of quartz and feldspar. It is everywhere highly altered, and in the vicinity of Diamond Hill quartz veins of microscopic and megascopic size ramify it. In general, the felsite to the south is lighter green in color than that to the north, and where it is partly replaced by silica, it is light brown in color, resembling a fine-grained sandstone in appearance. The felsite just south of the Massachusetts-Rhode Island State line resembles a green schist, it being very dark green in color, with occasional patches of chlorite. It is cut by calcite veins which vary in width up to one-eighth of an inch.

The unsilicified felsite of Diamond Hill is a dark greenish rock of aphanitic texture. Under the microscope it is seen to consist of a fine, indefinite mixture of feldspar and quartz, chlorite, calcite, sericite, and magnetite, sprinkled with grains of epidote. With this material are grains and patches of coarser epidote and an occasional phenocryst of plagioclase and quartz. The feldspar phenocrysts are badly altered and can not be determined very accurately, but may be as basic as andesine. A part of the quartz may be secondary.

The felsite from near the Massachusetts-Rhode Island line consists of feldspar and femic constituents or their alteration products and a minor amount of quartz. The feldspar appears to be oligoclase. Epidote is not present to any extent, but magnetite and calcite are, the chlorite often occurring in patches evidently secondary after some original femic constituent. Near the outcrop of this felsite is another of a light pinkish color. It is essentially aphanitic in texture, but shows a few phenocrysts of albite-oligoclase feldspar and quartz; also patches of chloritic material. It is also considerably altered.

Northeast of Grants Mills is developed what appears to be a flow of felsite which has incorporated a great number of angular fragments of felsite—a felsite flow breccia. The fragments vary in size, one-quarter of an inch being perhaps an average size. The rock is badly weathered, films of limonite being developed about the felsite fragments, so that they can be easily separated from the matrix. Farther north is a sheared phase of the same rock.

It appears that these felsites represent a series of flows from a fissure or fissures or a central vent probably located under Diamond Hill. The flows are of slightly varying composition (rhyolitic or dacitic), as indicated by their microscopic characters, and they were in all probability extruded in Wamsutta (Lower Pennsylvanian) time and presumably had a much wider extension formerly than at present. The contact between the Narragansett series is not exposed and it is therefore not certain whether the flows are interbedded with this series or not. Felsite does occur interbedded with the sediments at a point several miles away (see below). Neither can the direction of the flows be very well determined.

Wamsutta volcanoes.—Woodworth found a series of interbedded diabases and felsites in the Wamsutta formation of the Narragansett series. These outcrop around the margin of the horseshoe-shaped fold in which the Wamsutta is exposed. The felsites are found near South Attleboro, the diabases from North Attleboro to South Attleboro, and around the horseshoe up toward Arnold Mills; also there are some amygdaloids as exposed near 158 Elm Street, North Attleboro. Later studies have shown that these igneous rocks are probably surficial lava flows. Woodworth says:

“The peculiar features of the Wamsutta series—the rapid thickening of the sandstones and conglomerates toward the northwest corner of the present area, the felsites with definite flow structure, the gray ash beds or Attleboro sandstone, the agglomerates composed in large part of felsite pebbles—all point to a volcano or volcanoes existing in this field in Carboniferous time.”⁴⁷

Woodworth concluded that the source of these volcanics was probably from vents now occupied by the granite porphyries in Cumberland. It seems more probable, however, that this series of lava flows represent local fissure eruptions. Diamond Hill is composed of felsite of similar age to that at South Attleboro, but the distance between these two places is over 6 miles. Furthermore, the stratigraphic distance is 7 or 8 miles because of the folding of the Narragansett series. Therefore it seems best to explain the South Attleboro felsites and diabases and the Diamond Hill felsites by local fissure eruptions of contemporaneous age.

⁴⁷ Monograph U. S. Geol. Survey 33, p. 155.

MIDDLE PENNSYLVANIAN

Riebeckite-ægirite granite.—West of Diamond Hill, on Copper Mine Hill, is a considerable mass of alkaline granite with which is associated granite porphyry as a contact phase. A small boss of the same granite outcrops 2 miles north of the main mass. Several quarries have been opened in the granite, the most accessible of them being situated about a mile northwest of Diamond Hill.

The fresh granite is a medium, inclining to a fine-grained rock of a light gray color, with often a slightly bluish or greenish shade. In addition to its granitic texture, it possesses a slightly gneissoid structure. Megascopically it consists of distinct, gray or slightly bluish or greenish-gray unstriated feldspar crystals which will average not far from 2 millimeters in length by somewhat less in width; quartz, for the most part finely granular (sugary) in character; abundant small, black, lustrous prismoids of black hornblende, and less easily detected particles of dark-green ægirite. The hornblende grains are sometimes nearly as large as the feldspar, though in general smaller. The dark minerals possess a certain amount of alignment through the rock, which is responsible in large part for the feeble gneissoid texture above noted. Grains of purple fluorite may occasionally be detected. With a pocket lens many minute scales of a bright brownish yellow (dull brown in weathered specimens) mineral can be seen which the microscope shows are astrophyllite.³¹ The smaller grain of the quartz and hornblende relative to the feldspar, as the result of movement or crushing, produces the effect of a porphyritic texture, and indeed some portions of the rock, probably from its marginal parts, seem to have originally possessed a porphyritic texture. In the writers' opinion, however, the rock as a whole is not correctly defined as having a porphyritic texture, though Emerson and Perry³² apparently call it a porphyry.

In altered specimens the quartz is often stained yellow, as are also to some extent the feldspars, while the hornblende, etcetera, have gone over to magnetite and other ferruginous products.

Thin-sections examined under the microscope show that the minerals present are microcline micropertthite, quartz, riebeckite, and ægirite, with astrophyllite, fluorite, zircon, ilmenite (?), and a leucoxenic (?) material as accessories. The micropertthite is an albite-microcline intergrowth and possesses much the same characteristics as that of the well known Quincy granite to the north. The intergrowth appears in general, however, to be

³¹ Some biotite occurs, but this is pretty certainly the remnants of small inclusions of schist, diorite, or granite.

³² Op. cit., p. 53.

somewhat more patchy in character, and albite is not in general developed about the margins of the grains to the same extent as in the Quincy granite;³³ albite in separate crystals about the larger feldspars is also of rare occurrence. The microcline member is somewhat altered and shows, as compared with the albite, a marked tendency to include microliths of riebeckite and ægirite, which are abundant in the feldspar, as is the case in the Quincy granite and such rocks generally. Of all the minerals present, the micropertthite is the most nearly automorphic, the crystals showing a rather strong tendency toward rectangular forms, although the margins, if originally well defined, which is doubtful, have been destroyed by shearing.

Quartz, in grains comparable in size with the feldspar, may sometimes be seen, but even these show very broken extinctions, and most of the quartz is in the form of granular mosaics or streaks of small grains. The riebeckite sometimes forms good sized, irregular crystals, but is generally in smaller irregular prismoids or splinters and commonly shows a strong tendency toward subparallel aggregation, doubtless a result of movement. It is always of the strongly absorbing, pleochroic variety, deep blue or bluish green to black for the rays near c' and b , yellow or greenish yellow for the ray near α . The extinction is small (6 degrees to 8 degrees) on the cleavage. In short, it appears to be the same riebeckite that has been described in the Quincy granite.³⁴

The pyroxene appears to be a pure ægirite and is closely associated with the riebeckite, sometimes in parallel intergrowth with it, but more often irregularly grown into or upon it in the form of small prismoids, often with a subradial arrangement.

A mineral having the characteristics of astrophyllite or a closely related species is an important and quite abundant accessory. It is found in the form of slender plates or fibers about the riebeckite and ægirite, between their grains, along their cleavages, or penetrating the crystals irregularly; a small amount is found alone lying along the boundaries of the feldspar and quartz grains. It sometimes forms minute clusters and stellate groups. With its bright colors, yellow to orange, and marked micaceous habit, it is a striking constituent of the rock. While this mineral is a rare constituent of the Quincy granite, it is here very abundant and is perhaps the leading peculiarity of this granite.

Zircon is present, but comparatively rare, at least in a form that can be positively identified. Fluorite, on the other hand, is common and may

³³ C. H. Warren: Petrology of the alkali-granites and porphyries of Quincy and the Blue Hills, Massachusetts. Proc. Am. Acad. Arts and Sci., vol. 49, No. 5, 1913, p. 213.

³⁴ Loc. cit., pp. 216-219.

be locally very abundant. While sometimes colorless, it is often of a deep purple color. It forms shapeless grains or aggregates and is commonly found in close association with the riebeckite and ægirite. It is also commonly found associated with a finely granular material whose exact character is somewhat in doubt. This material forms masses of minute rounded or irregular grains which rarely reach a diameter of 0.2 millimeter. They are colorless to pale yellow, are usually filled with dusty particles, possess a high index of refraction, a strong double refraction, and not infrequently an obscure fibrous, radiated structure. In reflected light they have the peculiar white color generally associated with leucoxenic material. This granular material is very closely associated with the ægirite and riebeckite, particularly along zones in which shearing seems to have been particularly strong. The grains appear sometimes to be a replacement of ægirite or perhaps of the riebeckite which occurs with it. In some instances black oxide particles are found in the granules. Though the properties described for this material are not very positive, it is thought that it is in the nature of a leucoxenic alteration³⁵ developed during the period of shearing, and is also very likely closely connected with pneumatolitic action prevailing in the granite at that time. In fact, the general textural appearance of the granite is such as to suggest that the shearing may have accompanied the intrusion and consolidation of the rock when mineralizers were still active, and that the granular material described, as well as the astrophyllite, were a product of this period which also affected the textural relations of the riebeckite, ægirite, and quartz.

Quantitative studies.—It has not been possible for the writers to make chemical analyses of the riebeckite rocks. However, a Rosiwal estimate of the mineral composition has been carried out on a large thin-section cut from a typical specimen of granite from one of the quarries. Although not as precise as could be desired, on account of the textural peculiarities of the rock, it will serve to show very well the approximate mineral composition, and from it has been calculated the approximate chemical composition. These are given below, together with a chemical analysis of the "riebeckite porphyry"³⁶ from the same mass, of the Quincy granite, and of the riebeckite granite from the Island of Sokotra.

³⁵ This identification is supported by the occurrence of titanite as an alteration product of the riebeckite in the Quincy granite (loc. cit., p. 217).

³⁶ The specimen on which this analysis was made is said by Emerson and Perry to have come from the "top of hill one mile northeast of Sneece Pond," which according to their map would seem to be in their "granite-porphyry" area. From their description and from the writers' acquaintance with the field, it would appear to be a granite porphyry representing (see later) a phase of the igneous mass occurring nearer the porphyry than the granite of the quarry whose composition has been estimated by us.

	I	II	III
Feldspar	48.9	55.6	52.6
Quartz	33.3	33.3	41.4
Riebeckite	8.5	} 9.6	6.0
Aegirite	7.0		
Accessories	2.3	1.5	....
Total.....	100.0	100.0	100.0
Sp. G.....	2.73	2.66	

	Ia	IIa	IIIa	IV
SiO ₂	74.9	74.86	78.49	73.01
Al ₂ O ₃	9.3	11.61	9.99	11.23
Fe ₂ O ₃	3.7	2.29	1.94	2.53
FeO	1.8	1.25	1.18	3.66
CaO .....	....	.41	.30	.75
Na ₂ O	4.0	4.30	3.74	5.56
K ₂ O	4.2	4.64	3.84	3.66
Rest	2.5	.81	.81	.88*
Total.....	100.0	100.17	100.29	101.28

I. Mineral composition by Rosiwal measurement of the riebeckite-aegirite granite of Copper Mine Hill, Rhode Island, United States of America.

II. Mineral composition of the Quincy, Massachusetts, United States of America. C. H. Warren, Proceedings of the American Academy of Arts and Sciences, volume xlix, number 5, September, 1913.

III. Mineral composition of the riebeckite-ackmite granite from Dahamis, Insel, Sokotra, Elemente d. Gesteinslehre, 1910, edition, page 86. Calculated from the analysis by the writers.

Ia. Chemical composition of the Copper Mine Hill granite calculated from I.

IIa. Chemical composition of the Quincy granite corresponding to the mineral composition shown in II.

IIIa. Chemical composition of the Sokotra granite corresponding to the mineral composition shown in III.

IV. Chemical composition of the "Riebeckite-porphyr" by J. H. Perry, Bulletin of the U. S. Geological Survey, number 311, page 66.

It will be seen from the above table that the granite of Copper Mine Hill, while about as siliceous as that of Quincy, is less rich in feldspar and considerably higher in riebeckite and aegirite. This depresses the amounts of alumina and alkalis, increasing somewhat the total iron. Compared with number IV, it will be noted that, while there are considerable differences, the silica values are not far apart; likewise total iron and alkalis. The riebeckite porphyry contains only riebeckite, and therefore ferrous iron should be relatively higher in this rock and lower in the

* MnO = 0.19, MgO = 0.02, BaO, H₂O, etcetera.

granite with its abundant ægirite, which appears to be the case. A similar variation has been noted in the Quincy granite as compared with its fine granite and porphyry phases.³⁷ The Sokotra granite, though higher in silica and somewhat lower in total iron, is still strikingly similar in general character. The very low lime and magnesia are striking characteristics of all three.

A few quartz veins, up to a foot in width, are found in the granite and these often carry considerable fluorite. One small vein (one inch) of riebeckite has been noted.

Crocidolite from Beacon Pole Hill, occurring in masses up to an inch or more in diameter, associated with dolomite, quartz, and fluorite, has been described by A. H. Chester and F. I. Cairns,³⁸ who give an analysis. According to this, it corresponds quite closely to the riebeckite of the Quincy pegmatites.³⁹

As variations from the normal type above described we may note the occurrence, on the northwest side of the main mass, of a more coarsely crystalline variety in which crystals of riebeckite measuring up to 2 centimeters in length and 0.7 millimeter in breadth and large quartz crystals are present. This coarser phase appears in places to occur in the normal granite in the form of irregular patches.

Two miles south of Iron Mine Hill, on the road to Cumberland village, an intensely sheared phase of the granite occurs. Thin-sections show only riebeckite with the crushed micropertthite and quartz.

Inclusions.—In one of the quarries several inclusions were found, one of which is unmistakably a fragment of the near-by biotite granite. Another has been so largely recrystallized that its original character is rather doubtful. The granite inclusion, though somewhat modified, possesses the mineral and textural features belonging to the biotite granite, but now contains considerable fluorite derived from the inclosing granite. The other inclusion is now largely a mass of biotite flakes, recrystallized feldspar, quartz, and fluorite. The finding of the granite inclusion is of great importance, for it shows conclusively that the alkaline granite is intrusive into the biotite type. This relation is also borne out, as will be noted later, by similar inclusion in the riebeckite porphyry dike near Sneece Pond and by the actual chilled contacts of the riebeckite porphyry against the Milford granite.

Riebeckite-bearing granite porphyry.—A riebeckite-bearing granite porphyry outcrops in several localities: in the Cumberland dike west of

³⁷ Loc. cit., p. 295.

³⁸ Am. Jour. Sci., vol. 34, 1887, p. 108.

³⁹ Proc. Am. Acad. Arts and Sci., vol. xlvii, No. 4, July, 1911, p. 154.

Sneech Pond, in an irregular patch a mile farther east, in a small knob on Hunting Hill, and on a small hill west of Hunting Hill. Emerson and Perry found a dike of somewhat similar character near Lonsdale, 4 miles southeast of Albion.

The Cumberland dike is about 75 feet wide and about a mile long and of steep dip. It is intrusive into the Ashton schist, except at its southern end, where it cuts the quartzite. Small inclusions of the schist are abundant near the walls of the dike and some quartzite inclusions are also present. The dike shows but little chilling at the contact, and, as noted by Emerson and Perry, fluorite is often abundant in the sediments at the contact. In one place, where the road from Arnolds Mills cuts through the dike, a quartz vein a foot wide is exposed for a distance of nearly 50 feet along the strike of the dike. Part of the quartz is filled with long, slender needles of blue riebeckite (crocidolite) and furnishes very attractive specimens. Fluorite is often abundant as dark purple masses up to $1\frac{1}{2}$ centimeters in diameter. With the fluorite are a dark sphalerite, galena, and chalcopyrite, the latter crusted with covellite. The same sulphides associated with fluorite, it is interesting to note, are also found in quartz veins and in the pegmatic phases of the Quincy granite.

The specimens of the porphyry from this dike examined by the writers show a dark gray rock containing rather abundant round, smoky to blue quartz phenocrysts and rectangular feldspars embedded in a dark, fine-grained groundmass. The porphyry has been strongly sheared, giving the impress of a flow structure. The phenocrysts of feldspar, so far as seen, are a microperthite (pretty strongly altered), although Emerson and Perry⁴⁰ state that they have observed soda orthoclase; also phenocrysts filled with crystallizations of acid plagioclase. The groundmass in all of the specimens examined by us consists of a fine mixture of microperthite and quartz in which there is a great amount of magnetite in clustered masses of small grains and as separate grains and dust; also much calcite and other secondary products. Fluorite is always present. A small amount of what appears to be aegirite remains and some riebeckite may be seen in sections from some of the outcrops, but practically all of the soda-iron silicates have gone over to magnetite. The habit of the magnetite suggests that riebeckite was strongly predominant.

In the irregular mass of porphyry one mile east of Sneech Pond the quartz phenocrysts are rather larger than in the dike, and with the less conspicuous feldspar crystals lie in a fine groundmass which is highly altered and, besides quartz and feldspar, contains magnetite, sericite, calcite, and a greenish-brown secondary biotitic product.

⁴⁰ Loc. cit., p. 52.

The contact with the Milford biotite granite is well exposed at various points south of Copper Mine Hill and is a chilled contact. For over an inch from the contact the rock is very dark in color and perfectly dense; then quartz phenocrysts appear, but the rock does not assume its customary texture for about 5 inches. In the porphyry are many stringers of pre-Cambrian schist. In one of these inclusions is found a part of a labradorite porphyry dike.

An analysis of the porphyry from this neighborhood has been made by J. H. Perry and has been quoted and commented on above under the description of the granite.

The granite porphyry on Hunting Hill and on the hill to the west are essentially alike that just described. The rocks are badly altered and

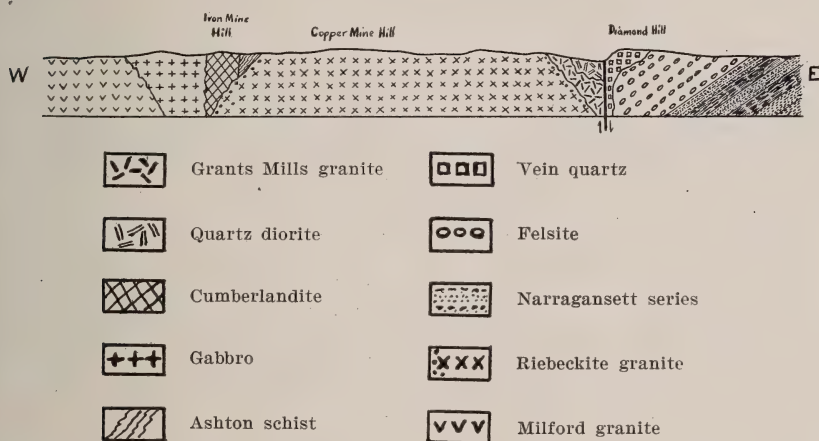


FIGURE 2.—Geological Section through Copper Mine Hill

See AA on map, page 437

consequently show now no riebeckite nor ægirite, but in their place is found abundant magnetite, together with other alteration products. The phenocrysts of micropertthite are fairly abundant, the quartz being usually larger than the feldspar.

From the mineral and textural character described and from their field relations, it seems clear to the writers that the riebeckite-ægirite rocks represent the upward projections of a single intrusion of a siliceous alkaline magma, and that the porphyritic phases represent simply the more quickly cooled marginal facies of the magma. Around the margin of the granite, as on the southeast, the rock becomes a porphyry. The granite and porphyry cut only the pre-Cambrian metamorphics and the granite of the Milford type. The stock does not appear to have been

uncovered until after Carboniferous times; at least no fragments of it have been identified in the conglomerates of the Narragansett series.

The accompanying sections, AA and BB, will serve to convey the authors' conception of the structure relations of the riebeckite and associated rocks.

The mineral composition of the riebeckite-*agrite* rocks here as well as their mode of occurrence are closely analogous to those of the Quincy-Blue Hille batholith 20 miles to the north, as well as to a small intermediate mass at Rattlesnake Hill, Sharon, Massachusetts,⁴¹ and there can be no doubt that the two masses possess a similar origin and history and are of the same age of intrusion. The Quincy mass is later than the Middle Cambrian and earlier than the Norfolk Basin conglomerates of Carboniferous age. If the three occurrences are of the same age, we have proof now that they are later and cut the biotite granite series, just as the similar alkaline rocks to the north of Boston cut the biotite granite (Saugus) of that region. The age of the alkaline granites is apparently the same as that of the Sterling granite of southern Rhode Island, the younger series of granites of western Massachusetts, and the alkaline granites of northeastern Massachusetts. As shown by Loughlin,* the Sterling granite cuts the Kingstown series of the Narragansett Basin, which is the equivalent of the Pawtucket formation on the north, and pebbles of the granite are found in the Dighton conglomerate. The diastrophism which accompanied the intrusions of these various batholiths took place in Middle Pennsylvanian time, as is shown both in Nova Scotia and New Brunswick (above the Mispec, Riversdale-Union and Coal Measures) and in the Narragansett Basin.

⁴¹ In the fall of 1912 Dr. F. H. Lahee called the writer's attention to the occurrence at Rattlesnake Hill, Sharon, Massachusetts, about 10 miles southwest of the Blue Hills and an equal distance northwest of Diamond Hill-Cumberland area, of a hitherto unknown small stock of riebeckite granite. This occurrence has since been studied by Messrs. W. L. Whitehead and R. C. Foster under the direction of Doctor Lahee and the writer, and the results were incorporated in thesis for the bachelor's degree in geology.

Their report may be summarized as follows: A coarse-grained riebeckite granite identical with the Quincy granite in general appearance and in mineral composition, except that no *agrite* is present, occurs on Rattlesnake Hill. This is surrounded on all sides by a fine-grained granite of the same composition, the whole forming a roughly circular mass about one mile in diameter. Contacts are not exposed, but the mass is surrounded on all sides by a biotite granite of the type found in Weymouth and Dedham. The coarse and fine granite appear to blend rapidly into one another. Occasional pegmatitic spots are found with very coarse riebeckite crystals.

There can be no doubt that in this mass we have another upward extension (cupola) of the alkaline granite magma more largely developed to the north in Quincy and the Blue Hills and to the south near Diamond Hill, Rhode Island. The riebeckite granite of Sharon is almost identical, so far as can be told without an analysis, with the fine granite of eastern and southern Quincy and northern Weymouth, and there appears to be no doubt but that the relations of the coarse and fine granite in the two localities are identical.—C. H. WARREN.

* Am. Jour. Sci., vol. 29, 1910, pp. 447-457, and vol. 32, 1911, pp. 17-32.

Diamond Hill quartz deposits.—This hill is undoubtedly the most striking geologic feature of the whole area. On the west the hill rises abruptly from a flat valley to a height of 280 feet. Its western top forms a jagged, picturesque ridge, barely covered by a scanty growth of small brush. The whole hill covers about one-third of a square mile, and of this at least one-third is either quartz or highly silicified felsite. To the east of the ridge, which is quartz, the hill slopes off rather gradually and is made up of felsite more or less cut by quartz veins for some distance away from the main center of silicification. The hill was briefly referred to by Woodworth in his report on the Narragansett Basin and was made the subject of a careful study by Messrs. R. A. Barber and H. S. Mears.⁴²

The western third of the hill is practically a replacement of felsite by quartz largely in the form of veins. These vary in width from those of microscopic dimensions to those 5 inches in width, and many of the

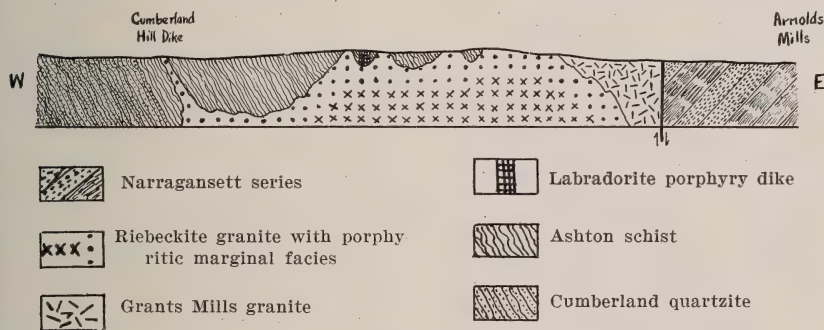


FIGURE 3.—Geological Section through Cumberland Hill

See BB on map, page 437

larger ones are of great length. While these have a very distinct trend parallel to the longer axis of the hill, they may be found running in all directions and, with innumerable ones of smaller size, form a most intricate and amazing network of veins. Their directions seem to have been determined by the jointing and fracturing of the rock.

The quartz is chiefly of the milk-white variety. In the veins, the crystals grow perpendicularly to the walls, giving rise to comb structures and very often with central vugs. In these the crystals are beautifully terminated and, as the rock commonly breaks along the line of these vugs, natural surfaces are covered with a mass of small quartz crystals which glisten like diamonds in the sunlight—a phenomenon that has given the hill its appropriate, though to the non-mineralogical mind a misleading, name. There are often successive layers of crystals separated at times by

⁴² Unpublished thesis. Mass. Inst. Technology, Boston, Mass., May, 1906.

thin films of red iron oxide. Iron oxide films a millimeter or more thick sometimes cover the quartz crystals in the vugs, and there is sometimes a segregation of the same along the sides of the veins in what was originally fragments of the felsite. There is, besides, a more or less general staining of the silicified felsite inclosed between the veins. The iron oxides are in part turgite, in part goethite, with perhaps some hematite and limonite. Under the microscope the quartz is typical vein quartz, often containing minute black specks or fine dark dust. Every stage in the replacement of the felsite by the quartz may be seen. Sericite and kaolin appear as products in the replacement. The iron oxide is probably residual from the felsite, although some of it may have been introduced by the siliceous waters. Sulphides are not now found, but were doubtless present, as they are found in other quartz veins in the neighborhood, and by their oxidation may have furnished part of the iron oxides. Some chalcedonic and opaline silica are found in fissures and lining pockets on the top of the hill, and jasper agate is reported by Kunz⁴³ as occurring on the hill in comparatively large amounts. At the southern end of the hill, where a railroad cut has been made, a coarse granite of the biotite type occurs in contact with the felsite. This has also been almost completely silicified, so much so that the actual contact with the felsite is obscured. A number of quartz veins run out for great distances into the granite at the eastern base of the hill, as well as into the felsite on the western side.

Another feature of mineralogical interest is the frequent occurrence in the quartz of casts of square, rectangular, or tabular outlines. These are surrounded by combs of quartz crystals and an incrustation of the same occurs on the walls of the casts. The casts will measure from one-quarter to three-quarters of an inch on a side. All of these have been identified as casts of barite crystals by Prof. Charles Palache, of Cambridge.

The injection of the quartz at Diamond Hill evidently took place after the granitic intrusion in Middle Carboniferous time. Toward the end of the mountain-building movements a north-south faulting occurred along the western edge of Diamond Hill. This faulting was accompanied by a brecciation of the felsite and the development of north-south fissures. Up these fissures came hot silica-bearing solutions, presumably the pneumatolitic fraction of the adjacent granite magma. The quartz, then, represents the dying phase of igneous activity in this locality. The quartz replaced the felsite where the brecciation was greatest and forced its way through the adjoining rock. It is very noticeable that the silicification was largely confined to the felsite, which was more easily fractured than

⁴³ Min. Res. U. S., 1893-1894, p. 749.

the granite on the west side of the fault. The quartz veins found in other near-by localities, some of which attain a considerable size, can be dated as contemporaneous with the silicification at Diamond Hill.

Determinations of the silica percentages of the altered and unaltered felsite show the extent of the replacement. The quartz rock on the west face of the hill contains 98.6 per cent SiO_2 ; the brown altered felsite contains 95.7 per cent SiO_2 ; the felsite just east of the zone of maximum silicification shows 76.5 per cent SiO_2 , and the normal felsite 68.7 per cent SiO_2 .⁴⁴ This low silica percentage indicates that the rock is an apodacite, the average SiO_2 per cent of dacite analyses being, according to Daly,⁴⁵ 66.9 per cent. Together with the chemical evidence concerning the nature of the rock is the petrographic evidence of the small amount of original quartz and the large amount of plagioclase feldspar and femic minerals, now highly altered. Therefore the rock may be classed as an apodacite.

Woodworth in his report on the Narragansett Basin briefly mentions Diamond Hill, ascribing the origin of the quartz to the action of hot springs following the decadence of igneous activity in the region. He dates the quartz veins in Wamsutta time, but the lack of metamorphism of the quartz veins indicates that they were not injected until toward the close of the orogenic movements in Middle Pennsylvanian time.

Two similar deposits of quartz have been described by G. F. Loughlin in Bulletin 492 of the U. S. Geological Survey. The principal one is at Lantern Hill, Rhode Island, and the other is at Swanton Hill, North Stonington, Connecticut. The origin of the quartz in Lantern Hill is a replacement of alaskite by pneumatolytic action. The quartz occurs in distinct veins with well developed comb structure in a very similar manner to that at Diamond Hill. The veins of the former deposit sometimes contain a few irregular crystals of pink feldspar. The quartz is filled with dirty specks and fluidal inclusions very much as that of Diamond Hill.

The Diamond Hill quartz has been quarried for a number of years. The crushed and powdered quartz has been used for road metal, poultry grit, roofing gravels, fireproof brick and fire sand. It is now used as crushed stone for concrete and is being mined in a large cut in the west side of the hill.

Sheldonville quartz vein.—A short distance north of the village of Sheldonville, Massachusetts, and 3 miles northeast of Diamond Hill is a mineralized quartz vein which first attracted attention about 1896, and

⁴⁴ Analyses by Barber and Mears in 1906.

⁴⁵ Average chemical composition of igneous rock types. Proc. Am. Acad. Arts and Sci., vol. 45, No. 7, 1910.

was subsequently exploited for copper, silver, and gold, but has for some time been abandoned. It is claimed that two carloads of picked ore running some 9 per cent in copper and with small values in silver and gold were at one time shipped from the vein. It is exposed for 380 feet and attains a width of 12 feet. Its strike is north 6 degrees west, dip 45 degrees west. There are a number of smaller veins in the immediate vicinity.

The vein cuts the Joes Rock granite and an inclusion of the pre-Cambrian schist has been encountered in the mining operations. The Carboniferous conglomerate has also been found near the vein. This indicates that the present surface of the land at this point was also the Middle Carboniferous land surface invaded by the sea which deposited the Wamsutta conglomerates. The highly weathered character of the granite and of the schist inclusion support this view. The composition of the red Carboniferous sediment at its contact with the granite shows that the former was a residual deposit derived from the latter. The quartz vein coming in after the deposition and consolidation of the Carboniferous sediments has a very fresh appearance, forming a marked contrast to the deeply weathered and altered granite and green schist.

The vein has been opened at several points, in one place by a shaft 100 feet deep, and its character is well exposed for observation. The quartz is, where not stained by oxidation of the iron-bearing sulphides, of the milky white variety, is distinctly banded, and often shows comb structures with small vugs. A number of minerals are found in the quartz, either as scattered crystals or as small veins between the layers of quartz. Pyrite is the most abundant mineral, with chalcopyrite next. Sphalerite, galena, pyrrhotite, tetrahedrite, siderite, limonite, and turgite have been noted. Small cross-cutting veins of chalcopyrite and galena occur. Although fabulous values in silver have been reported, an assay made on a carefully taken sample⁴⁶ showed only 40 cents in silver and a trace of gold.

A similar quartz vein 2 miles east of Sheldonville, cutting the same biotite granite, has been exploited for gold and silver. These and many of the other smaller veins of quite similar general characteristics are all referred to the same period of silica deposition as the Diamond Hill quartz lode.

POST-PERMIAN DIABASE DIKES

In the area discussed in this paper there are a few diabase dikes, some of which are the youngest rock in the region. Such dikes are frequent in

⁴⁶ Lord and Gregory: Unpublished thesis in mining engineering. Mass. Inst. Technology, 1909.

New England, and their age is usually considered as Triassic. There is probably another older series of similar dikes, judging by the extensive alteration of some of them. In the Blue Hills, near Quincy, Massachusetts, there are diabase dikes which cut Middle Cambrian slates, but which are older than the pre-Carboniferous riebeckite granite.

Several diabase dikes occur in the vicinity of Iron Mine Hill cutting the pre-Cambrian schists and the gabbro. In the northeastern corner of the area, south of Uncas Pond, is a dike cutting Joes Rock quartz porphyry. Boulders have been found in which diabase cut riebeckite granite; therefore some of the dikes must be younger than those of the Blue Hills, and it seems best to refer them to the Triassic.

SUMMARY

The geological history of this region as now exposed begins in pre-Cambrian times with the deposition of what is now the Cumberland quartzite. With this sediment were deposited beds of shale until finally the sedimentation was entirely of shale, with some conglomerate composed largely of pebbles from the earlier sandstone. A small amount of limestone is interbedded with the shale. A part of the schist is probably of igneous origin. After the close of the sedimentation, masses of gabbro and probably the cumberlandite, with accompanying dikes of labradorite porphyry, were intruded into the sediments.

A period of diastrophism followed the pre-Cambrian sedimentation and initiated Lower Cambrian sedimentation, only two remnants of which are now exposed—at Hoppin Hill and south of Joes Rock.

During the Acadian revolution of Middle Devonian age the biotite granites were intruded, accompanied by quartz diorites and fine granites or fine granite porphyry as facies of the main intrusion. At the beginning of Pennsylvanian time the deposition of the Narragansett and Bellingham series of shales, conglomerates, and sandstones with interbedded volcanics commenced. In Middle Pennsylvanian time a period of diastrophism interrupted the sedimentation. The riebeckite granites were intruded, followed by the injection of quartz veins at Diamond Hill. Sedimentation recommenced with the deposition of the Dighton conglomerate of the Narragansett Basin, but was brought to a close by the Appalachian revolution. Since this time the region has been one of erosion. A few diabase dikes were intruded probably in Triassic time.

The various sedimentary and metamorphic-sedimentary rocks have been briefly described. A summary description has also been given of the gabbro and the ultra basic rock, cumberlandite. A megascopic and micro-

scopic description of the biotite granites found in the area is given. On the basis of field relations and of the general mineralogical and textural similarity of the unshered phases of these granites, they are all believed to form parts of one batholith—the Milford batholith. Local facies, quartz diorites, and fine granite or fine granite porphyries are briefly referred to.

The riebeckite-ægirite granites and porphyries are described and shown to be of strikingly different texture and mineral composition, as well as of later age, than the biotite granite series. They form a single intrusion and the porphyries appear as the marginal chilled phase of the invading mass. They are correlated with the closely similar granites and porphyries found in larger development in the Blue Hills and Quincy, and form, so far as known, the southernmost extension of the great series of rocks characterized by the presence of microperthitic feldspars and highly alkaline hornblendes or pyroxenes, or both. The occurrence of a smaller intermediate mass of the same type at Rattlesnake Hill, in Sharon, recently discovered by Dr. F. H. Lahee, is noted as forming still another upward protuberance of the alkaline magma.

THE SOLAR HYPOTHESIS OF CLIMATIC CHANGES ¹BY ELLSWORTH HUNTINGTON ²*(Read before the Society January 1, 1914)*

CONTENTS

	Page
Introduction.....	479
Geological importance of study of present climatic changes.....	479
Hypotheses in explanation of present climatic changes.....	481
The meteorological hypothesis.....	481
The volcanic hypothesis.....	483
The solar hypothesis.....	484
General discussion.....	484
Disagreement between solar and terrestrial temperature changes.....	485
Present status of the solar hypothesis.....	486
Newcomb's conclusions as to temperature.....	486
Relation of temperature changes during sun-spot cycle to glaciation.....	490
Apparent contradictions between temperature changes in dif- ferent parts of the world.....	491
Effect of Arctowski's pleions on the distribution of temperature..	492
Cyclonic storms within the tropics.....	493
Continental <i>versus</i> marine climates in Europe during the sun-spot cycle.....	494
Cyclonic storms in temperate latitudes.....	497
Researches of Professor Kullmer.....	497
Cyclonic storms during the sun-spot cycle.....	501
Kullmer's law of the shift of the storm track.....	502
Shifting of storms in the main storm belt.....	510
A test of the shifting of storm tracks by means of correla- tion coefficients with sun-spots.....	513
Cyclonic storms and volcanic eruptions.....	515
Shifting of the storm track in Europe.....	517
The "cyclonic" <i>versus</i> the "caloric" form of the solar hypothesis..	521
The reduction of terrestrial temperature by cyclonic storms....	522
A possible magnetic or electric cause of cyclonic storms.....	524
The climate of historic times.....	526
General discussion.....	526

¹ Manuscript received by the Secretary of the Society July 10, 1914.² With the cooperation of Charles J. Kullmer and E. E. Free.

	Page
The trend of opinion as to the climate of the past.....	526
Progressive desiccation during historic times.....	527
Climatic uniformity during historic times.....	528
Climatic pulsations during historic times.....	529
Trees as a climatic yardstick.....	529
Climatic pulsations according to critics of the hypothesis of progressive desiccation.....	532
Objections to the hypothesis of climatic changes.....	534
Ancient droughts and famines.....	534
The existence of deserts in ancient times—Alexander's march...	534
The distinction between changes of temperature and changes of precipitation.....	536
Examples of large variations in rainfall accompanied by slight variations in temperature.....	538
Diversity of changes of climate in different regions.....	539
The shifting of climatic zones—Penck's hypothesis.....	540
Possible explanations of historic changes of climate.....	544
The meteorological hypothesis.....	544
The volcanic hypothesis.....	544
The solar hypothesis.....	544
General discussion.....	544
The United States.....	545
Asia.....	549
Europe.....	549
The probability of great changes in sun-spots in the past.....	552
Pettersson's sun-spot hypothesis.....	552
The scarcity of early sun-spot data.....	553
Major sun-spot cycles of the present time.....	553
The nature of sun-spots.....	555
The connection between historic changes of climate and the Glacial period.....	556
Complexity of post-Glacial climatic variations in the Southwest....	556
Free's data as to old strands in the Southwest.....	558
The inclosed lakes of Asia.....	563
The causes of the Glacial period.....	565
General discussion.....	565
The carbonic acid hypothesis.....	566
The cyclonic solar hypothesis.....	567
General discussion.....	567
The double storm belt in America.....	568
The glacial storm belts of Europe.....	572
The effect of the glacial storm belts on temperature and precipitation.....	572
The glacial precipitation of the Alps.....	574
The distribution of loess.....	575
Permian glaciation.....	578
General discussion.....	578
The effect of precipitation on temperature.....	579

	Page
The effect of a Permian cloud blanket in low latitudes.....	580
The blanketing effect of clouds at present.....	581
The Permian desert in the north.....	587
Conclusion.....	589

INTRODUCTION

In the study of glaciation and of other ancient climatic phenomena it has been tacitly assumed that changes of climate in the geological past have been due to causes which are not now in operation, or whose effects during the past few generations have been so small that they have escaped observation. This is a natural assumption. In the first place, the phenomena of the last Glacial period, which may serve as the standard example for all the main climatic changes, are so vastly greater than anything that we can now observe that the mind naturally supposes them to have been due to some cause of correspondingly grand proportions. In the second place, the phenomena of that period have appeared to be wholly different from anything now occurring. No one, for instance, has hitherto described any modern occurrences corresponding to the glacial accumulation of snow in Labrador and Scandinavia, or to the apparently coeval aridity which gave rise to loess in the Mississippi Valley and central Europe. In the third place, meteorologists have insisted that their records give no support to the idea of any recent changes of climate greater than the little fluctuations which every one notices from decade to decade. They have expanded this into the doctrine that the present causes of climatic instability are not competent to produce anything more than temporary variations, which disappear within a few years. In view of this, geologists have apparently had no choice except to assume that Glacial periods, epochs of aridity, and the other main climatic vicissitudes of the remote past have been phenomena distinct from anything that we can now actually observe.

GEOLOGICAL IMPORTANCE OF STUDY OF PRESENT CLIMATIC CHANGES

Two lines of recent study suggest that there may possibly be ground for modifying this commonly accepted opinion. In the first place, meteorologists and climatologists have of late become more and more convinced of the instability of all climatic conditions. Cycles of 11 and 35 years are now accepted by numerous students. Many phenomena in central and western Asia, the American Southwest, California, North Africa, and Central America seem to suggest that cycles lasting hundreds of years

may be the rule in all parts of the world. This opinion is, of course, open to question; but even those who oppose the idea of any permanent change during historic times are willing to accept the idea of cycles with a duration of centuries.³ So careful and conservative a climatologist as Hann, the author of a work on Climatology which is universally accepted as a standard, is convinced that, in central Asia at least, the climate has changed during the past two thousand years.⁴ In the second place, various lines of evidence, part of which have been presented elsewhere⁵ and part of which will be presented here, seem to show that present variations of climate are connected with solar changes much more closely than has hitherto been supposed. Moreover, these changes, in spite of their short period, show a considerable number of phenomena which display a striking similarity to the vastly greater phenomena of Glacial periods.

In view of these facts, it is not impossible that the cause of glaciation, or at least an important contributory cause, may be discovered by a study of present climatic variations. Accordingly, the first portion of this paper will be devoted to an investigation of the causes of present climatic variations—a line of study which leads at once to a consideration of the possible relationship between terrestrial climate and the activity of the sun's surface. The object before us is primarily geological, but in treating this part of our subject we shall be obliged to follow meteorological methods. By so doing we shall be prepared to take up the purely geological phases of the matter, for the facts here presented suggest strongly that the present is the key to the past.

That the climate of the earth varies from year to year needs no demonstration. The variations can readily be seen in equatorial and polar regions; they become more pronounced in the subtropical zone, and they reach their highest development in the temperate zone of cyclonic storms. The first step in obtaining a satisfactory knowledge of climatic variations of all kinds, whether large or small, would seem to be to ascertain the cause of such differences between the weather of one year and another. Three hypotheses seem to be worthy of consideration. The first is the common meteorological explanation. The second is the new hypothesis of volcanic dust. The third is the solar hypothesis, which has hitherto been somewhat indefinite. Let us consider each of them in detail.

³ For instance, in the *Geographical Journal* for 1914 J. W. Gregory and P. Kropatkin advocate the hypothesis of climatic uniformity and of progressive desiccation, respectively, but both admit cycles having a duration of centuries. In the *Annales de Géographie* for 1914 Herbetton makes a similar admission, although he strongly opposes the present author's general conclusions as to pulsatory climatic changes.

⁴ J. Hann: *Klimatologie*. Stuttgart, 1908, vol. 1, p. 352, note.

⁵ Ellsworth Huntington: *The Climatic Factor*. Washington, 1914.

HYPOTHESES IN EXPLANATION OF PRESENT CLIMATIC CHANGES

THE METEOROLOGICAL HYPOTHESIS

No one can doubt the importance of purely meteorological causes in producing the climatic variations which we observe from year to year. The annual change in the sun's altitude from season to season sets in motion a train of consequences which can scarcely act in precisely the same way each year. Accidental circumstances, such as the veiling of certain areas by clouds, slight alterations in the strength or course of oceanic currents, and many other circumstances, all may, and indeed must, occur. If several accidents happen to lead in the same direction, we may have a winter of unusual warmth or a summer with more than the usual rainfall. Therefore students of meteorology and climatology almost universally believe that purely meteorological causes are adequate to produce a large part of the variations by which the weather of one year differs from that of another. A few hold that such fortuitous causes may produce marked variations lasting scores of years. None, however, maintain that they are the cause of great climatic changes lasting through long periods. Hence this hypothesis would have little importance from the geological point of view were it not that it has led geologists to search for the cause of glaciation in conditions whose operation can not now be observed. Because of this effect it seems necessary to consider the matter somewhat further.

Two important lines of reasoning seem to indicate that although the hypothesis of purely accidental meteorological variations may explain many minor phenomena, it does not fully explain the larger variations from year to year. In the first place, the vast majority of climatic vicissitudes in temperate regions are due to variations in the number and location of cyclonic storms. These in turn, as the Indian Meteorological Service has shown,⁶ are associated with distinct and systematic changes in the winds, which cause the equatorial rainfall of Abyssinia and the Nile floods on the one hand, and the monsoon rains of India on the other hand. Cyclonic storms, as will soon be shown in detail, are probably the climatic phenomenon which varies most markedly in harmony with sun-spots. Hence there may be ground for the opinion that although these occurrences are apparently accidental, they are probably not really so.

The second reason for not accepting the purely meteorological hypothesis, except in respect to minor phenomena, lies in the fact that the

⁶ *Memoirs Indian Meteorological Department*, vol. xxi, part vii, 1913. The cold weather storms of northern India, by G. T. Walker.

See also part ii, p. 34, in the same volume.

very essence of accidents is that they should not occur regularly, and that the same kind of accident should not occur throughout a large part of the world again and again at the same time. Yet this is exactly what occurs, as is clear from the painstaking sifting of climatic records carried on by Arctowski. As I have discussed his work in "The Climatic Factor" (pages 243 ff.), I shall here merely sum up the results there set forth. It should be added, however, that since that volume was written further investigation has led to the conclusion that changes of solar temperature, as distinguished from other solar changes, may perhaps be less important than at first seemed probable. The work of Arctowski is of unusual importance because of his extremely accurate and detailed methods, and because he has branched out into certain new and suggestive lines of research. One of his chief pieces of work has been a most careful analysis of variations of temperature apart from those due to the seasons. After eliminating all possible effects of seasonal changes, he finds that essentially the same series of slight departures from the normal mean temperature is found in widely remote areas, including much of the southern and oceanic part of the torrid zone and the great continental interiors of the northern hemisphere. These are the parts of the world where the climate is most directly under the immediate control of solar radiation. In other regions, where the temperature is largely influenced by the heat carried by ocean currents and winds, Arctowski's curves show that the same variations occur, but that they are either more or less masked and so appear smaller than elsewhere, or else show a lagging which seems to be due to the fact that heat is transported from other regions. Leaving these doubtful cases out of account, however, we seem justified in concluding that the systematic recurrence of the same variations of temperature in cycles having a length of about two years, more or less, in regions as diverse as Peru, South Africa, Madagascar, Mauritius, Java, Ceylon, New York, the interior of Russia, and the Arctic Ocean is not in harmony with any theory which appeals to purely accidental agencies pertaining to the earth's own atmosphere and determined by local conditions. Such variations can only occur under the impulse of some widely acting cause which must be world-wide in its effect.^{6a}

^{6a} See Henryk Arctowski: A study of the changes in the distribution of temperature in Europe and North America during the years 1900 to 1909. *Annals of the New York Academy of Sciences*, vol. 24, 1914, pp. 39-113. In this publication, which did not come to hand until the present paper was in print, Arctowski gives abundant reasons for believing that some cause of extra-terrestrial origin is constantly giving rise to short-lived variations of temperature. In certain regions, such as those mentioned in the text, the variations are of the Arequipa type, while elsewhere the peculiar conditions of topography, winds, and currents cause them to be reversed. When a "pleion" or "antipleion"—that is, an area of excess or deficiency of temperature—is once formed

THE VOLCANIC HYPOTHESIS

We turn next to the highly geological hypothesis of volcanic dust as the cause of climatic variations. It owes its importance to Abbott and Fowle,⁷ working together on the one hand, and to Humphreys,⁸ working by himself on the other hand. These authors seem to have shown almost beyond doubt that volcanic eruptions of the explosive type are responsible for a slight lowering of the earth's temperature. Their results are summed up in figure 1, which is taken unchanged from Humphreys. The upper curve shows the amount of solar radiation which actually reaches the earth, as measured by the pyrheliometer. The next curve is that of sun-spots inverted. The third will be described in a moment, as will also the fourth. At the bottom the chief explosive volcanic eruptions are indicated. In general the eruptions appear to be accompanied or closely followed by a fall in the pyrheliometric curve, thus indicating that the volcanic dust cuts off a small part of the solar radiation. The fourth curve, marked "temperature departures," shows the average amount by which the temperature of a number of selected stations departed from the normal from 1880 to 1912. The stations were widely distributed, but were confined to equatorial regions or else to continental interiors—that is, to the parts of the earth where the temperature depends most directly on the sun and is relatively little influenced by winds and currents. These, it will be remembered, are the regions where Arcowski finds his synchronous variations of temperature in a two and a half year cycle. This cycle does not appear in figure 1 because this is based on annual means, and the cycle is so short that it can be detected only by the use of monthly means. An inspection of figure 1 shows that the temperature curve does not agree with that of the pyrheliometer. In 1903 and 1912, however, both are at a minimum, which suggests that they are influenced by a common cause. The low places in the pyrheliometric curve in 1885 and 1891 occur one and two years, respectively, *after* the minima of the temperature curve to which they are supposed to give rise. Moreover, the maxima of the two curves do not agree at all closely. The most probable conclusion seems to be that the presence of volcanic dust in the upper atmosphere is of real importance in determin-

it swings back and forth across its continent, or even out into the ocean, and carries conditions of high or low temperature with it. Such pleions or anti-pleions may last for years, and may diminish in force and again be rejuvenated.

⁷ C. G. Abbott and F. E. Fowle: *Volcanoes and climate*. Smithsonian Misc. Coll., vol. 60, 1913, 24 pp.

⁸ W. J. Humphreys: *Volcanic dust and other factors in the production of climatic changes and their possible relation to Ice ages*. Bulletin of the Mount Weather Observatory, vol. 6, part 1, 1913, 26 pp.

ing the temperature of the lower air, but that other causes are of much greater importance.

THE SOLAR HYPOTHESIS

General discussion.—Having reached the conclusion that, although both purely meteorological and volcanic causes of climatic variations are

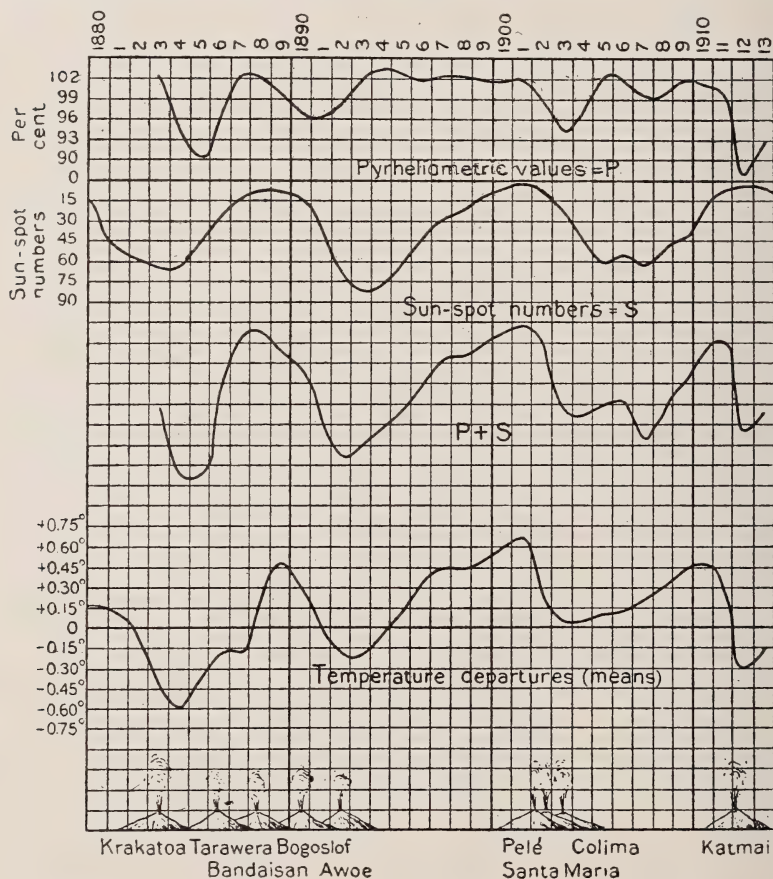


FIGURE 1.—Solar Heat, Sun-spots, Terrestrial Temperature, and Volcanoes
(After Humphreys)

actually in operation, they are probably of relatively minor importance, we are prepared to turn to the solar hypothesis. It is most interesting to see that Abbott and Fowle and also Humphreys, in spite of their natural enthusiasm over the discovery of a new factor in the determination of climate, have not attempted to assign to it a major rôle. They have been compelled to turn to the solar hypothesis. The second curve from the

top in figure 1 shows Wolfer's sun-spot numbers inverted. A comparison of this with the curve of temperature departures shows considerable agreement. Nevertheless there are also pronounced discrepancies. Recognizing this and also feeling convinced of the importance of solar radiation, our two sets of authorities have both adopted the same method. They have combined the pyrheliometric curve with that for sun-spots. The result is given in the third curve, $P + S$. This agrees with the temperature departures much more closely than does either of the other curves. Apparently, if we judge from the curves of figure 1 alone, the earth's temperature depends on at least two primary factors: first, the type of solar activity indicated by sun-spots, and, second, the amount of solar heat which can reach the earth's surface through an atmosphere which is sometimes relatively clear and at others more or less filled with dust. Between the two factors, as appears in figure 1, there seems to be a great difference, for changes of temperature seem to agree with variations in solar spottedness much more closely than with volcanic eruptions.

Disagreement between solar and terrestrial temperature changes.—At this point attention should be directed to a somewhat striking phenomenon. Few people would question that if the sun should become notably warmer or cooler the earth's temperature would also change. This conclusion, apparently inevitable, is the basis of the ordinary form of the solar hypothesis of climatic changes. Yet in figure 1 we see that the actual measurements of the radiation received from the sun do not agree with the temperatures recorded in the parts of the earth's surface where the sun is able to act most effectively. The changes in the amount of solar radiation which gets through the atmosphere and reaches the earth's surface appear to have a distinct effect, as is evident from the fact that the $P + S$ curve is more like the temperature curve than is the simple S curve which represents sun-spots alone. Yet apparently there is some other solar factor whose influence on changes of terrestrial temperature is much greater than that of variations in the amount of solar heat.

This conclusion is emphasized by another fact. Abbott⁹ states that the net result of observations made by the Smithsonian Institution and by other agencies during a long series of years is to show that during years of maximum sun-spots the solar constant is higher than during years of minimum spots. This is exactly contrary to the conditions of terrestrial

⁹ C. G. Abbott: Science, vol. 39, 1914, p. 347. "An increase of a hundred sun-spot numbers corresponds to an increase of about 0.07 per square centimeter per minute in the solar radiation outside the earth's atmosphere." Abbott gives the mean value of the solar constant as 1.933 calories. Since sun-spot maxima at present range from sun-spot numbers of about 45 to 155, this means that during the sun-spot cycle the solar constant may be from 1.6 per cent to 5.6 per cent greater at sun-spot maxima than at minima.

temperature, as is evident from the fact that in figure 1 the sun-spot curve has had to be inverted in order to correspond to the temperature curve. This does not mean that the slight additional heat received from the sun during times of many sun-spots does not produce its due effect in warming the earth. It merely suggests that at the times when the sun is active and is unusually well supplied with spots *two* agencies are at work in modifying the earth's temperature. One of these is the increased temperature of the sun's surface; but the effect of this is so small that it is not merely nullified, but actually reversed by the other agency. What that other agency may be we must now proceed to investigate.

The experiences of every day show that the temperature of any part of the earth's surface depends on two chief factors: One of these is the amount of heat received from the sun; the other is the winds, which not only act directly, but which cause ocean currents, and thus transport large bodies of heat from equatorial regions to places such as the North Atlantic and western Europe. If variations in the actual mean temperature of the sun are too small to be of appreciable importance, as they seem to be, the winds remain as by far the most important determinant of variations in terrestrial temperature. Their importance seems greater than is often realized, for they carry heat from place to place not only horizontally, as is universally recognized, but also vertically—a fact which people who are not meteorologists are apt to lose sight of. The intensity of both kinds of movement may and does vary. Our task will be to see what connection this appears to have with changes in the sun and then with possible causes of glaciation.

Present status of the solar hypothesis—Newcomb's conclusions as to temperature.—Before proceeding to this task, it is necessary to obtain a clear conception of the exact status of our present knowledge of the relation of sun-spots and climate and of the reasons for and against believing that any relation really exists. In considering this the reader must remember that previous studies have been based on the natural assumption that if such a relationship exists it must be due to changes in solar temperature. According to the hypothesis here to be developed, on the contrary, it may be due merely to a redistribution of the present amount of heat, both horizontally and vertically.

One of the most thorough investigations of the relation of solar and terrestrial phenomena was made by Newcomb.¹⁰ His conclusions are based on a comprehensive study of terrestrial temperatures at periods of

¹⁰ A search for fluctuations in the sun's thermal radiations through their influence on terrestrial temperature, by Simon Newcomb. Trans. Am. Phil. Soc., n. s., vol. 21, 1908, p. v.

maximum as compared with minimum sun-spots. His figures can scarcely be questioned, although his theoretical conclusions are not equally convincing. His main conclusion is expressed as follows (page 379):

"A study of the annual departures [from mean temperature] over many regions of the globe in equatorial and middle latitudes shows consistently a fluctuation corresponding with that of the solar spots. The maximum fluctuation in the general average is 0.13°C . on each side of the mean for tropical regions. [The maximum temperature comes at times of minimum sun-spots.] The entire amplitude of the change is therefore 0.26°C . [0.47°F .], or somewhat less than half a degree of the Fahrenheit scale."

Several points in this conclusion deserve emphasis. In the first place, Newcomb does not stand alone. Köppen¹¹ has made a similar study, although not quite so exhaustive. His conclusion agrees with that of Newcomb. He finds that at the equatorial stations which he made use of the difference between the temperature at periods of maximum and minimum sun-spots amounts to 0.75°C ., while in temperate latitudes it decreases and becomes less and less noticeable, the average being 0.54° for regions beyond the tropics. The variations of temperature within the tropics may be seen in the following table, which shows the amount by which the mean temperature for individual years of the sun-spot cycle is above or below the mean for a long series of years. The table is that of Köppen, but it has here been copied from Hann's *Klimatologie*, volume 1, page 356:

TABLE 1

Variations of Mean Temperature within the Tropics in the Sun-spot Cycle

Sun-spot minimum (approximately)	+0.33° C.	Sun-spot maximum (approximately)	—0.32° C.
1 year after minimum....	+0.15	6 years after minimum...	—0.27
2 years after minimum...	—0.04	7 years after minimum...	—0.14
3 years after minimum...	—0.21	8 years after minimum...	+0.08
4 years after minimum...	—0.28	9 years after minimum...	+0.30
		10 years after minimum..	+0.41

The maximum temperature comes about 0.9 of a year before the sun-spot minimum, while the minimum temperature practically coincides with the maximum of sun-spots.^{11a}

¹¹ W. Köppen: Über mehrjährige Perioden der Witterung ins besondere über die II-jährige Periode der Temperatur.

After this paper was in type there came to hand an important article by Köppen (W. Köppen: Lufttemperaturen, Sonnenflecke und Vulcanausbrüche; *Meteorologische Zeitschrift*, vol. 7, 1914, pp. 305-328). In this he reviews his former conclusions on the basis of a greatly increased body of meteorological data, most of which have been arranged by J. Mielke (*Archiv der Seewart*, Jahrgang 1913; Hamburg, 1914). All parts of the world where records are available have been considered, and the data cover

For polar regions we have as yet no good compilation of data. If the decrease, which both Newcomb and Köppen notice as one passes away from the equator, continues indefinitely poleward, it would appear that in polar regions the difference between periods of sun-spot maximum and minimum may almost disappear. The importance of this will appear later. Other authorities, as well as the two just mentioned, have found differences in terrestrial temperature corresponding to variations in sun-spots. For example, Arctowski,^{11b} shows that according to his geographical method the difference between the mean temperature of the earth in 1893, a year of maximum sun-spots, and in 1900, when the spots were almost at a minimum, amounted to about 0.5° C. The agreement among the various authorities is so complete that we may safely consider that the relation of solar changes and terrestrial temperature is an established fact. This, however, does not necessarily prove that the earth's climate is appreciably influenced by changes in the amount of heat emitted by the sun. Newcomb holds that this is not the case, and Hann, the great authority on climate, is inclined to agree with him, although he expresses

the century from 1811 to 1910. Hence the results are even more reliable than those of Newcomb. They are summed up in the following table:

Departures from Mean Temperature during the Sun-spot Cycle

Year of sun-spot cycle.	Torrid Zone.	South Temperate Zone.	North Temperate Zone.	World (lands).
Approx. sun-spot minimum..	+0.36° C.	+0.23° C.	+0.31° C.	+0.32° C.
1 year after minimum.....	+0.11	+0.08	-0.04	+0.11
2 years after minimum.....	+0.07	+0.03	0.07	+0.07
3 years after minimum.....	-0.11	+0.03	-0.07	-0.08
4 years after minimum.....	-0.23	-0.20	-0.06	-0.13
Approx. sun-spot maximum..	-0.11	-0.20	-0.12	-0.14
6 years after minimum.....	-0.13	-0.03	-0.08	-0.11
7 years after minimum.....	-0.11	-0.08	-0.20	-0.16
8 years after minimum.....	-0.13	-0.04	0.07	-0.04
9 years after minimum.....	+0.02	+0.00	-0.04	-0.02
10 years after minimum....	+0.24	+0.25	+0.07	+0.18

These figures agree with those quoted above except that the amplitude of the change of temperature from maximum to minimum is somewhat less. Köppen shows further that the new figures strengthen the conclusion that the variation during the sun-spot cycle is most regular and of greatest amplitude in the tropics, while in the far north, although it can still be detected, it is unimportant and there are often contradictions. Another important matter is that, so far as the data go, there does not seem to be a compensation of low temperature in one region by high temperature in another. Inasmuch as the data cover only about one-sixth of the earth's surface, the rest being either water or lands where no data are available, this can not be regarded as positive proof that the mean temperature of the earth's surface as a whole actually suffers a reduction at times of many sun-spots, but it points in that direction. When one sun-spot cycle is compared with another, Köppen does not find reason to think that the mean temperature varies in harmony with the range of spottedness—that is, when the difference between maximum and minimum spots is great, there does not seem to be a correspondingly great difference in the mean temperature. In support of this he gives the

himself guardedly. On page 341 of the work already cited, Newcomb says:

"Although the reality of this 11-year fluctuation [both solar and terrestrial] seems to be beyond serious doubt, the amplitude being several times its probable error, its amount is too small to produce any important direct effect upon meteorological phenomena."

Again, on page 384, he puts in italics the last part of the following quotation:

"It follows as the final result of the present investigation that *all the ordinary phenomena of temperature, rainfall, and winds are due to purely terrestrial causes, and that no changes occur in the sun's radiation which have any influence upon them.*"

Newcomb's opinion carries great weight. Nevertheless, while his conclusions as to the difference in temperature between periods of maximum and minimum sun-spots seem to be unassailable, his conclusion as to changes in meteorological phenomena stands on quite a different basis. It

following table, which I have modified so as to place the sun-spot cycles in the order of their intensity.

First year of sun-spot cycle.	Difference between maximum and minimum sun-spot numbers.	Difference between temperature at times of maximum and minimum spots.		
		A North Temperate Zone.	B Tropical Zone.	C South Temperate Zone.
1833.....	126	2.2	5.1	...
1867.....	126	-0.1	1.7	2.9
1844.....	116	0.5	1.5	2.2
1855.....	88	2.8	1.2	2.0
1889.....	80	0.6	2.4	1.7
1822.....	61	1.4	2.4	...
1878.....	59	1.8	2.1	1.3
1811.....	45	3.2	...	...

In the north temperate and tropical zones the table supports Köppen's conclusion, but in the south temperate zone there is a perfectly regular decrease in range of temperature in harmony with the decrease in range of spottedness. The north temperate and tropical zones contain large masses of land, and the figures for temperature represent the conditions as influenced by the irregular circulation and other peculiar conditions of continents. The south temperate zone contains so little land that it may be regarded as representing marine conditions. If similar conditions are characteristic of the ocean as a whole—except in the parts where large bodies of heated water are brought in from other latitudes—the mean temperature of the entire earth would probably rise and fall in harmony with the sun-spots, not only when parts of the same sun-spot cycle are compared, but when different cycles are compared.

The last part of Köppen's paper is devoted to a discussion of the effect of volcanoes on temperature. He comes to the conclusion that no important effect seems as yet to be proved. He bases this chiefly on the fact that if volcanic dust is a main factor in causing a reduction of temperature, years showing a large minus departure of temperature ought to be more numerous than years showing a large plus departure. The contrary is the case.

¹¹⁶ Henryk Arctowski: *L'Enchainement des variations climatiques* Bruxelles, 1909.

is an inference, and he does not go into details to demonstrate its truth. He has apparently failed to consider two important matters. One is the effect which even a slight change of temperature may have on meteorological conditions, provided it be permanent. The other is the possibility that while the *mean* temperature of the earth's atmosphere may vary only slightly, the *distribution* of temperature may vary considerably. In other words, he has not considered the possibility that the mechanism whereby solar heat is distributed may be so altered that the air at high altitudes or in tropical latitudes may become warmer or cooler, while that at low altitudes or in polar regions may suffer the opposite change. This might occur without any appreciable change in the mean temperature of either the earth as a whole or the sun. To put the matter in another way, certain climatic phenomena, such as cyclonic storms and their attendant winds, may change their intensity and location, and may thus alter the distribution of temperature without any great change in mean temperature, provided all parts of the atmosphere are averaged together. The possibility of this depends entirely on the cause of storms, a matter as to which we are still in doubt.

Relation of temperature changes during sun-spot cycle to glaciation.—Turning now to the first objection to Newcomb's conclusion, let us consider the true importance which a range of 0.26°C . between the temperature at times of maximum and minimum sun-spots would have, provided the temperature did not fluctuate between the extremes every 11 years, more or less, but remained constant at one extreme for a few centuries. As I have discussed this matter in detail elsewhere,¹² I shall here merely summarize that discussion.

The usual estimates of the change of mean temperature from the height of the Glacial period to the present time range from 3°C . to 11° . The average is 5° or 6° . This means that the best authorities hold that a change of temperature amounting to only about 24 times the change that now takes place from periods of sun-spot minimum to sun-spot maximum sufficed to cause the difference between an epoch when ice covered all northwestern Europe and the northern United States, and the present epoch, when the ice has retreated almost entirely, except in Greenland and Antarctica. If the conditions which Newcomb states to be those characteristic of periods of minimum sun-spots should prevail steadily for a few centuries and then should give place to those characteristic of periods of sun-spot maxima for an equal length of time, the climate of the world would be so altered that it would have gone one twenty-fourth

¹² The climatic factor as illustrated in arid America. Pub. 192, Carnegie Institution of Washington, 1914, pp. 242-243.

of the way toward a Glacial period. To take a concrete example, the Rhone glacier is now, according to Geikie, barely 6 miles long; the foot of the ice stands at an altitude of 5,780 feet, and the surface near the head of the glacier is 10,200 feet above the sea. During the period of maximum glaciation the glacier was 240 miles longer than now; its foot stood about 4,700 feet below the present level, and the surface in the upper portions was 1,400 feet higher than today. It seems fair to assume that the results of a small change of mean temperature would be proportional to those of large changes. If this be so, the difference of 0.26°C ., which Newcomb finds between sun-spot maxima and minima, ought to produce a change in the ice equal to about 4 per cent—that is, one twenty-fourth—of the change since the height of the last Glacial epoch. In that case, if the form of its valley were favorable, the Rhone glacier might become 10 miles longer than it now is, or if the gradient of its valley bottom be assumed as uniform it might descend to a level 180 feet below that of the present ice-foot, or it might increase 56 feet in thickness. The exact nature of the change in the glacier and its exact dimensions would depend, of course, on the topography of the Rhone Valley and on the relation of precipitation to temperature, winds, and other meteorological phenomena. The figures which have just been given, however, show the order of magnitude of the results which might be expected from a lowering of the mean annual temperature of the earth to the extent of 0.26°C ., provided the change were permanent rather than temporary. A change of temperature capable of producing such results, or even results half as great, would scarcely seem to be too small to produce “any important effect on meteorological phenomena.” The truth of Newcomb’s conclusion appears to be at least an open question.

The other point which Newcomb has failed to consider, namely, the possibility of a change in the distribution of terrestrial temperature without a corresponding change in the mean temperature of the earth as a whole, will be taken up later. It is closely allied to another objection to the ordinary form of the solar hypothesis, namely, the improbability that the mean temperature of the sun can change so rapidly as to cause our terrestrial changes. Both of these matters will be discussed later, after we have considered the question of cyclonic storms.

Apparent contradictions between temperature changes in different parts of the world.—Leaving now the direct effects of temperature, let us consider the effect of movements of the air on temperature and on our view of the probability that solar changes are the cause of the variations of terrestrial climate. In the opinion of meteorologists, the greatest objection to the solar hypothesis is probably the numerous apparent con-

traditions which beset the path of the investigator. The general opinion may be expressed in the words of Hann:¹³

"The results of very numerous and complex investigations of the connection of the sun-spot period with variations of the meteorological elements have not wholly corresponded to expectations. The influence of the sun-spots on the meteorological elements has been proved as comparatively unimportant. Only in the most favorable cases is one in the position to consider that the traces of a parallel course in the progress of certain meteorological elements and in that of the sun-spot frequency is proved. There can be no thought of the prediction of the course of the weather on the ground of the sun-spot cycle."

From this broad statement Hann goes on to show that the amount of agreement between sun-spots and climatic phenomena varies greatly, according to the part of the earth and the precise climatic elements which are investigated. The reader who would carry the matter farther is referred to the last chapter of volume 1 of Hann's *Klimatologie* and to the large number of references there cited. In general, Hann unqualifiedly accepts the conclusions of Newcomb and Köppen as given above. He shows that aside from temperature the strongest evidence of a sun-spot cycle is found when a single element, such as summer rains or tropical cyclones, to take the best two examples, is considered alone, and when it is investigated by the use of means for a large number of stations and for long periods. When single stations or single sun-spot cycles are considered, there is likely to be no visible relation whatever. Such things as frosts do not seem to fit into the sun-spot cycle with any definite relationship, and there are often contradictory results when the same climatic element is investigated in different regions or different periods. In rainfall, as in temperature, there is decidedly more evidence of a sun-spot cycle within the tropics than in other parts of the world.

Effect of Arctowski's pleions on the distribution of temperature.—From what has just been said, it is evident that the temperate zone is the critical region. It is there that we find the contradictions which are the main objection to the solar hypothesis. Students of the question have apparently supposed that if the sun really does play an important part in determining terrestrial variations of temperature, this ought to be as evident in the temperate zone as in the torrid. The work of Arctowski, however, as I have shown in "The Climatic Factor" (pages 244-250), suggests that the apparent conflict between the evidence in equatorial and temperate regions is the expectable condition. For example, in the part of the torrid zone south of the equator his curves of fluctuations of temperature agree closely in all longitudes. Coming north to Bombay,

¹³ J. Hann: *Handbuch der Klimatologie*. Stuttgart, 1908, vol. 1, pp. 355-356.

however, we find the same periodicity as in the regions farther south, but with a lag of about a year. This is what would be expected in a region whose climate depends largely on the monsoons. These winds, as is well known, drive the waters of the southern Indian Ocean up into the Arabian Sea. They thus eventually bring to Bombay the heat which was originally accumulated in the broad oceanic regions farther south. Under such circumstances we should naturally expect that if the torrid zone were unusually warm at a certain period, no matter what might be the cause, the heat would be carried northward in such a way that the warmest time at Bombay would be later than in the more oceanic regions to the south, and thus we should get an apparent contradiction. Arctowski's work shows that similar contradictions are found elsewhere, in such regions as the West Indies and the neighboring coasts of Florida, where the influence of oceanic currents is particularly strong. In Europe, where the general type of climate is dominantly under the influence of winds which have been warmed by the waters of the Gulf Stream and its continuation in the Atlantic Drift, we should expect a still greater degree of lagging. If the torrid zone were warm during one particular year, the effect of that would presumably be felt in course of time in Europe. How great the delay would be we can not tell. Nansen¹⁴ has shown that "variations in the temperature of the Atlantic Current off the Norwegian coast from one year to another seem to be succeeded two years later by similar variations in the quantity of ice in the Barents Sea in the spring." This means that in this far northern region the heat which the Atlantic Drift and the Gulf Stream have brought in varying quantities from the torrid zone is carried along at the rate of much less than a thousand miles a year. In its earlier course the heat is carried faster; but as it travels from 7,000 to 10,000 miles, several years must be consumed in the journey. Under such circumstances it is clear that in Europe, where the subject has been most carefully investigated, we should fully expect that the conditions of temperature would be quite different from those of the torrid zone. Such a difference would neither prove nor disprove a possible relation between sun-spots and climate. This conclusion, if well grounded, removes one of the chief objections to the solar hypothesis.

Cyclonic storms within the tropics.—Having seen that, so far as temperature is concerned, there seems to be no good reason why we should not accept the solar hypothesis and many good reasons why we should, let us turn to some of the other climatic elements. The winds, as we have already seen, are by far the most important determiner of temperature, aside from the sun itself. In their investigation attention has been

¹⁴ F. Nansen: The sea route to Siberia. *Geographical Journal*, vol. 43, 1914, p. 492.

directed mainly to the general scheme of movements, and this has proved so complicated that relatively little is yet known of how the total movement of the air varies from year to year. This is true both of such regular phenomena as the trade winds and prevailing westerlies and of such irregular phenomena as cyclonic storms. Such storms prevail to a slight degree in equatorial regions, where they are known as tropical hurricanes, and to a high degree in temperate regions, where they are the element which adds constant variety to the climate of North America, Europe, and Japan. Quantitative measurements of the trade winds and westerlies for a series of years appear never to have been compiled, and the task is sure to prove difficult. Cyclonic storms, however, are recorded with accuracy by the various weather bureaus of the world. This is fortunate, for although among the least understood of climatic phenomena, they are among the most important. Each of the two types—that is, tropical hurricanes and the ordinary storms of the temperate zone—seems to show a close connection with sun-spots. Tropical hurricanes have been investigated in the Atlantic Ocean by Pocy and Fassig and in the Indian Ocean by Meldrum. Their number and intensity vary in harmony with the number of sun-spots. Wolf¹⁵ has compared the number of hurricanes with the number of sun-spots and gets the interesting result, shown in Table 2. Here we seem to have an unmistakable relationship:

TABLE 2

Number of hurricanes per year	Relative sun-spot numbers
1 and 2.....	17
3	59
4	62
5	70
6 and 7.....	80
8	88

Continental versus marine climates in Europe during the sun-spot cycle.—In temperate latitudes cyclonic storms are far more numerous and important than within the tropics. In fact they are the controlling element of the climate, and any changes which have occurred in the past must be closely associated with them. Unfortunately, the storms of Europe can not easily be investigated as yet, except for a short series of years, for the barometric records have not been charted in such a way as to show their movements. Later, in connection with the storms of America, we shall consider those recorded in Europe. For the present, however, let us turn to a new line of evidence which sheds light on climatic changes in quite a different way. In "The Climatic Factor" much space

¹⁵ J. Hann; *Klimatologie*, vol. 1, p. 360.

has been given to the investigation of the relation between climate and the rate of growth of trees. It has there been shown that if the proper methods are employed, even a small number of trees will give a fairly accurate record of the particular climatic elements on which growth chiefly depends. The method was first developed by Prof. A. E. Douglass, who measured the yellow pine in Arizona. His methods are described by himself in "The Climatic Factor." In Germany, at Eberswalde, near Berlin, he has made some measurements which are of importance in the present connection. The results are shown in figure 2. The lower curve is that of sun-spots. The curve above it shows the growth of thirteen pine trees. This has been smoothed to eliminate minor vagaries, but not in such a way as to influence the main sinuosities. It has also been corrected in order to eliminate the effect of the more rapid growth of trees

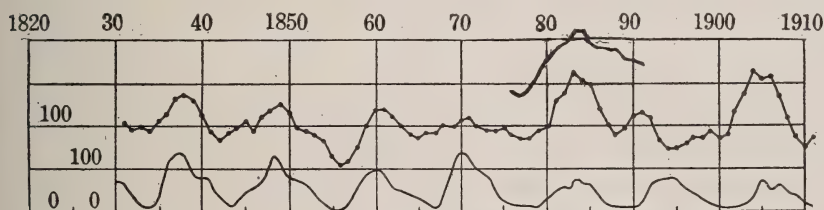


FIGURE 2.—*Growth of Trees at Eberswalde, Germany (middle curve), and Sun-spots (lower curve). (After Douglass)*

NOTE.—The small upper curve indicates the number of summer storms (April–November)

in youth than in maturity and old age. These processes have been discussed in full in "The Climatic Factor," and the reader who would understand them is referred to that publication. It will there be seen that the whole matter is mathematical, and that the personal opinion of the investigator can not materially influence the results. The extent to which the two main curves of figure 2 agree is remarkable. With one exception the seven maxima of the sun-spot curve are faithfully reproduced in the tree curve. The minima agree equally well. The only exception begins in 1892 and continues until 1899. It has not been possible to ascertain its cause. It may be due to some meteorological condition or to some such thing as insect pests. If the growth of the trees had not been checked, its curve would probably have agreed closely with that of the sun-spots. This conclusion is strengthened by the fact that in 1900 we have a little minimum corresponding to the minimum in the sun-spot curve, but occurring slightly before it, as is usually the case.

In order to determine exactly what climatic conditions are indicated by the tree curve of figure 2, I have worked out two sets of correlation

coefficients for each month of the year, one set being the relation of temperature and tree growth and the other rainfall and tree growth. A period of 50 years, 1851 to 1900, was used for rainfall, and 42 years, 1866 to 1907, for temperature, these years being determined merely by the records which happened to be at hand. The coefficients show that rapid growth depends chiefly on two conditions. The first is relatively high temperature in the late winter and early spring. The second is abundant rainfall from April to November. The amount of snow in the winter is of comparatively little importance except where it prevents the ground from warming up in the spring. The summer temperature also makes relatively little difference. These facts suggest that the most favorable conditions for the growth of trees in Germany are periods when rainfall is abundant during the summer and when the winters are comparatively free from storms and snow, so that the trees can begin their growth early in the season. The amount of rainfall in climates like that of northern Germany depends largely on the number of cyclonic storms, although in summer it is considerably influenced by minor showers which are not accompanied by pronounced barometric disturbances. In order to illustrate the relation of storms to the growth of the trees, I have added to figure 2 a little upper curve showing the number of storms from April to November, inclusive, during the period from 1876 to 1891, the only period during which such data are available. This curve is based on figures which have been kindly supplied by Prof. C. J. Kullmer. They include all the storms whose centers passed within $2\frac{1}{2}^{\circ}$ north or south of Eberswalde. The curve has been smoothed to correspond with the smoothing of the other curves. Its earlier portion probably falls too low; for, as Professor Kullmer points out, the records of storms in Europe during the early years of the present series are not particularly reliable. The curve thus obtained agrees in its main features with the curve of the trees. The agreement is not perfect, however; for other factors, such as the temperature of the early spring, play a part in determining the rate of growth. Nevertheless it is so close that we are possibly justified in concluding that the curve of tree growth shown in figure 2 represents the main fluctuations in the cyclonic storms of summer.

The curve of tree growth represents not only the number of summer storms, but also the conditions of the winter, as has already been said. Where the curve is high the months of February and March appear to have been fairly warm and dry. It will be noticed that these conditions—that is, abundant storms and rain in summer and an early heating up of the ground in the spring—are typical of continental climates. In oceanic climates, although the winters are on the whole warm and wet, the springs

are relatively cool and the summers are not apt to show markedly more precipitation than the winters. In view of this, then, we may interpret the curves of figure 2 as meaning that when sun-spots are numerous, relatively continental conditions of climate prevail in northern Germany. This carries with it the implication that at such times the continental areas of high pressure tend to become intensified in winter, so that the air blows outward from them and cyclonic storms are compelled to move along the margins of the continent rather than toward its interior. In summer, on the contrary, the low-pressure areas of the center of Eurasia appear to become intensified, and this causes the winds to blow toward the interior and to bring abundant moisture. The full importance of this will appear later, when we come to discuss changes of climate during the past two or three thousand years.

Cyclonic storms in temperate latitudes—Researches of Professor Kullmer.—We now come to much the strongest type of evidence as to cyclonic storms and their relation to sun-spots. Prof. Charles J. Kullmer,¹⁶ of the University of Syracuse, has made a careful investigation of the matter, both in the United States and Europe. His first work appears as a chapter in "The Climatic Factor," but since that was published he has gone into the matter much more thoroughly. From the maps of the United States Weather Bureau he has compiled monthly and yearly data from 1874 to 1912. Omitting the earlier years, where the degree of accuracy is not great, he has found the average for the 30 years from 1883 to 1912 and has thus prepared the accompanying map, figure 3. His method was to divide the United States and Canada into a series of rectangles, each of which extends $2\frac{1}{2}^{\circ}$ in latitude and 5° in longitude. He then counted the number of storm tracks passing through each rectangle during each month of the year. The total for the year gives the relative storminess. The figures for the various squares are the average values for 30 years. The map shows a pronounced bow-shaped area of great storminess swinging down from British Columbia into the northern United States, across the Great Lakes and down the Saint Lawrence Valley. A minor area of relatively high storminess is found in southeastern Colorado. The number of storms in one area as compared with another is not a measure of

¹⁶ In the remainder of this paper the name of Professor Kullmer will recur again and again. When the paper was originally written it was expected that before its publication Professor Kullmer's data would all have been published, but various unforeseen circumstances have prevented this. His results were given to the world, however, at the meeting of the Association of American Geographers at Princeton in January, 1914. Both before and after that meeting Professor Kullmer most kindly permitted me to make the fullest use of all his material. Now, with rare courtesy, he has permitted me to publish a large number of his maps and other data prior to the appearance of his own report. I can not too strongly express my appreciation of his great kindness.

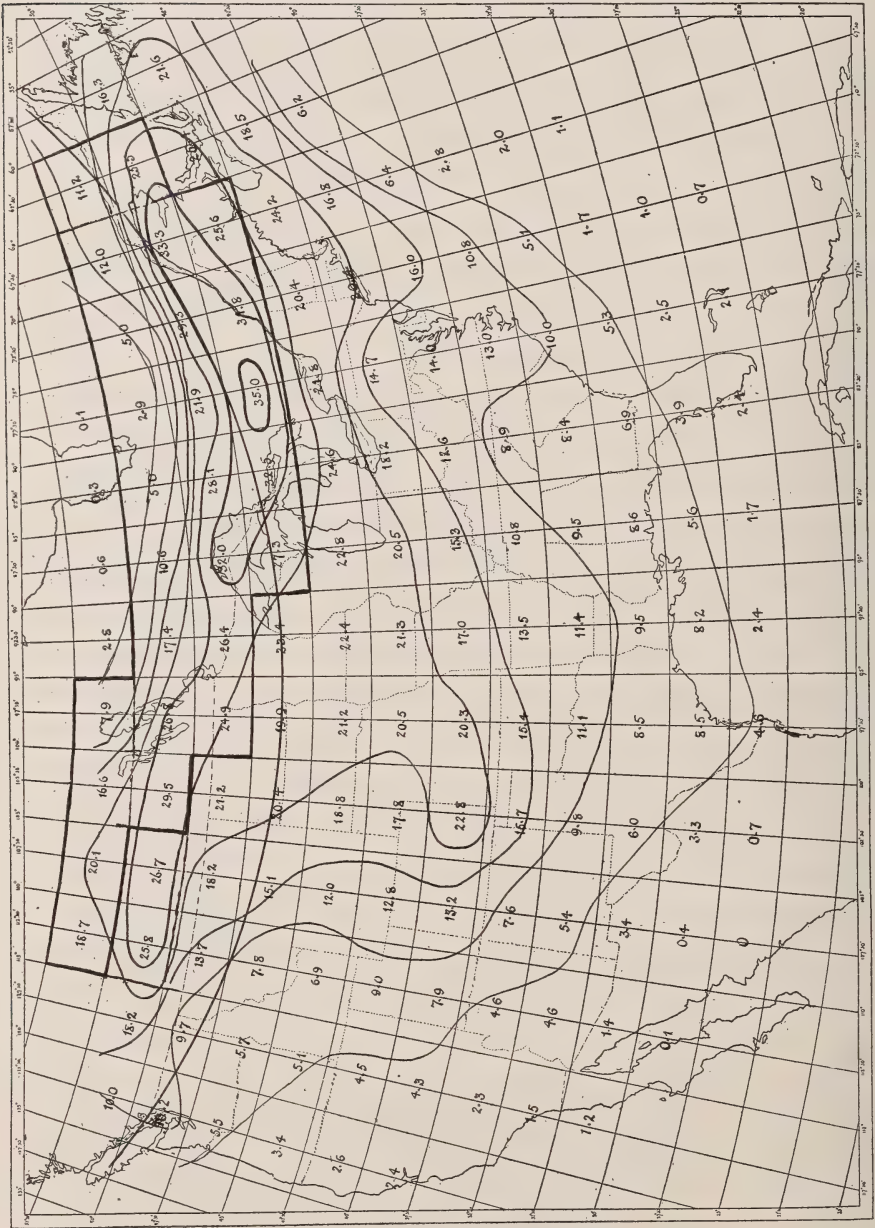


FIGURE 3.—*Storm Tracks in the United States*
Average number of storm centers crossing areas $2\frac{1}{2}^{\circ}$ in latitude and 5° in longitude each year during the thirty years from 1883 to 1912. (After Kullmer)

the amount of rainfall, since that is largely influenced by latitude, nearness to the ocean, the location of mountains, and other topographic considerations. When a given area is compared with itself at different periods, however, the number of storms is roughly proportioned to the rainfall up to certain limits, for the topographic conditions in any one place, of course, remain constant.

The data for storms in Europe are much less reliable than in America. The only available series of charts is that of the "Deutsche Seewarte," where, as has already been stated, the 16 years from 1876 to 1891 are included. Unfortunately, the maps for the different years are not homogeneous. The area which they cover varies. Moreover, in the later years the data not only cover a wider area than at the beginning, but barometric minima of smaller dimensions have apparently been included. The reason for thinking this is that if we take the area included in the first year and compare it with the same area in later years we find that the number of storms apparently increases enormously. This is illustrated in the following table:

TABLE 3

Storminess for Periods of 4 Years in Europe and America in per cent of Averages for 16 and 30 Years respectively

Years	Europe Per cent	America Per cent
1876-1879	67.5	89.5
1880-1883	103.0	79.0
1884-1887	104.3	90.0
1888-1891	123.8	99.9
1892-1895 .....	....	110.1
1896-1899 .....	....	103.0
1900-1903 .....	....	100.5
1904-1907 .....	....	105.7
1908-1911 .....	....	98.6

Here the 16 years have been divided into four groups, each containing four years. The average number of storms for the 16 years in the area covered by the first map is called 100 per cent. The figures show the number for each successive series of years. It will be seen that in the last group the number is almost twice as great as in the first. In America the figures are much more homogeneous, as appears in the same table, although here, too, the earlier years show a deficiency which is probably due to scarcity of observations. In the American figures for the first two groups of years allowance has been made for the fact that the data only extend as far west as the 100th meridian, while in later years the whole



FIGURE 4.—Storm Tracks in Europe

Average number of storm centers crossing areas $2\frac{1}{2}^{\circ}$ in latitude and 5° in longitude each year during the sixteen years from 1876 to 1891 (After Knutner)

country is included. Kullmer's map for storminess in Europe is given in figure 4. Here it will be seen that there are three areas of great storminess. One of these has its southern limit at the Hebrides Islands, and extends northeastward beyond the Arctic Circle and to the north of Europe. The second begins in southern England and extends northeastward so as to cover Holland, Belgium, northern Germany, southern Sweden and Norway, the Baltic Sea, and southern Finland. The third is of smaller size than the others. It is located in northern Italy and in the Mediterranean area just west of that region. It is probable that the intensity of the storminess here is exaggerated because of the sinuous character of the tracks in this region.

Cyclonic storms during the sun-spot cycle.—Before proceeding to a discussion of these maps let us ascertain to what extent the actual amount of storminess varies in harmony with the number of sun-spots. Let us take first the American data, since they are more reliable than those from Europe. The matter may be investigated in various ways. First, let us take the three years of fewest sun-spots, which in most cases would be the year of minimum spots and the years before and after, and let us compare these with the succeeding three years of maximum spots. This method is of especial interest, because these are the groups of years used by Kullmer in the highly significant maps which will shortly be presented. An inspection of the sun-spot curve of figure 2 shows that since storm records have been kept there have been three complete sun-spot cycles, all of which have been of mild intensity compared with their predecessors. In these we have three periods of minima and three of maxima. A comparison of the first two periods—the minimum of 1877-1879 with the maximum of 1882-1884—is of little value, since the records of these early years are not highly reliable, and since for the minimum period the data extend only to latitude 100° west. Coming to the next two periods—the minimum of 1888-1890 compared with the maximum of 1892-1894—we find that during the maximum the storminess was greater than during the minimum by no less than 14.3 per cent of the mean for 30 years. The storminess of the succeeding sun-spot maximum, 1905-1907, exceeded that of its preceding minimum, 1900-1902, by 1.4 per cent.

Let us now consider the matter in another way. Let us compare the complete sun-spot cycle from 1889 to 1900, inclusive, with the succeeding one from 1901 to 1911. Each of these begins with a sun-spot minimum and lasts until the year preceding the next minimum. The average sun-spot number for the 12 years of the first cycle was 38.8, and its storminess was 107.4 per cent of the average storminess for 30 years. The average sun-spot number for the 11 years of the second cycle was 33.3

and its storminess was 99.8 per cent. Evidently here, just as in the other case, when sun-spots were more abundant, storms were also more abundant.

There is still another method by which we may compare the number of storms with the sun-spot numbers. Let us divide the 30 years for which full records are available into six groups of five years each, according to the sun-spot numbers. The first group will be the years having the smallest sun-spot numbers, the next the five years having the next smallest sun-spot numbers, and the last the five years of most abundant spottedness. In the following table the first column shows the average sun-spot number for each group, and the second column the average storminess in percentages of the mean for 30 years. The third column will be described later:

TABLE 4

Average sun-spot number for five years	Percentage of storminess in North America	Percentage of stormi- ness in main storm area of North America
4.5	95.5	74.7
9.7	104.5	101.6
24.5	101.6	99.4
42.2	102.4	105.2
58.0	90.4 (102.2)	98.2 (101.0)
73.0	111.3	121.6

This table should be compared with that for tropical hurricanes on page 494. The storminess does not here increase with the regularity seen among hurricanes, although perhaps it would do so if the whole northern hemisphere were included. The chief irregularity is due to the group of five years having an average sun-spot number of 58. These were the years 1883, 1884, 1885, 1905, and 1906. The average storminess for 1905 and 1906 was 102.2 per cent, which is only slightly less than would be expected if there is a regular increase in proportion to the sun-spot numbers. The other three years, 1883 to 1885, were the first during which the part of the United States west of 100° west was included in the Weather Bureau's statistics of storms. It is probable that during these early years the data are incomplete, and hence that our table is to that extent inaccurate. If we omit this doubtful group, it appears that when sun-spots are least numerous storms are least numerous. With a moderate number of sun-spots, the storminess is close to the average, while with extreme spottedness the storminess greatly increases.

Kullmer's law of the shift of the storm track.—The apparent relationship between the number of storms and the spottedness of the sun is

probably of high importance, but neither its importance nor its verity can rival that of a most striking discovery made by Kullmer. He has ascertained that there is a definite law as to the shifting of storm tracks in response to changes in sun-spots. The American data, as has already been stated, cover three successive periods during which a group of three years of minimum spots may be compared with a similar and succeeding group of maximum spots. The periods are as follows:

(1) The minimum years of 1877, 1878, and 1879, compared with the maximum years of 1882, 1883, and 1884.

(2) The minimum years of 1888, 1889, and 1890, compared with the maximum years of 1892, 1893, and 1894.

(3) The minimum years of 1900, 1901, and 1902, compared with the maximum years of 1905, 1906, and 1907.

We may also make a fourth comparison by using the last sun-spot maximum and comparing it with the following instead of the preceding minimum. Thus:

(4) The maximum of 1905, 1906, and 1907, compared with the minimum of 1910, 1911, and 1912.

For each of these periods—that is, three maxima and four minima—Kullmer has found the total number of storms, and has thus obtained the figures for a series of maps similar to figure 3, except that each represents the average of three years instead of 30. He has then taken the map of a minimum series of years and that of the succeeding (or in the last case the preceding) maximum series, and has compared the two, square by square, to see to what extent the maximum years exceed or fall short of the minimum. The figures thus obtained have been plotted in another series of maps, two of which are given in figures 5 and 6. These represent the two groups of years marked (2) and (3) above—that is, the two which are most perfect and which do not overlap. The other two maps show the same features as these two and might equally well have been used. In the maps the plus sign means that the three maximum years had more storms than the minimum years, while the minus sign means that storminess was greater when the sun-spots were at a minimum. The numbers show the totals for three years, and must be divided by three in order to obtain the average for a single year. Lines have been added at intervals of five to bring out the essential features. Solid lines indicate that when the sun-spots were at a maximum the storminess was greater than when the spots were at a minimum, while dotted lines indicate the reverse. In figure 7 I have combined all four of Kullmer's maps into a single map, which shows the average difference between all the available years of sun-spot maxima and minima. Here the numbers indicate the

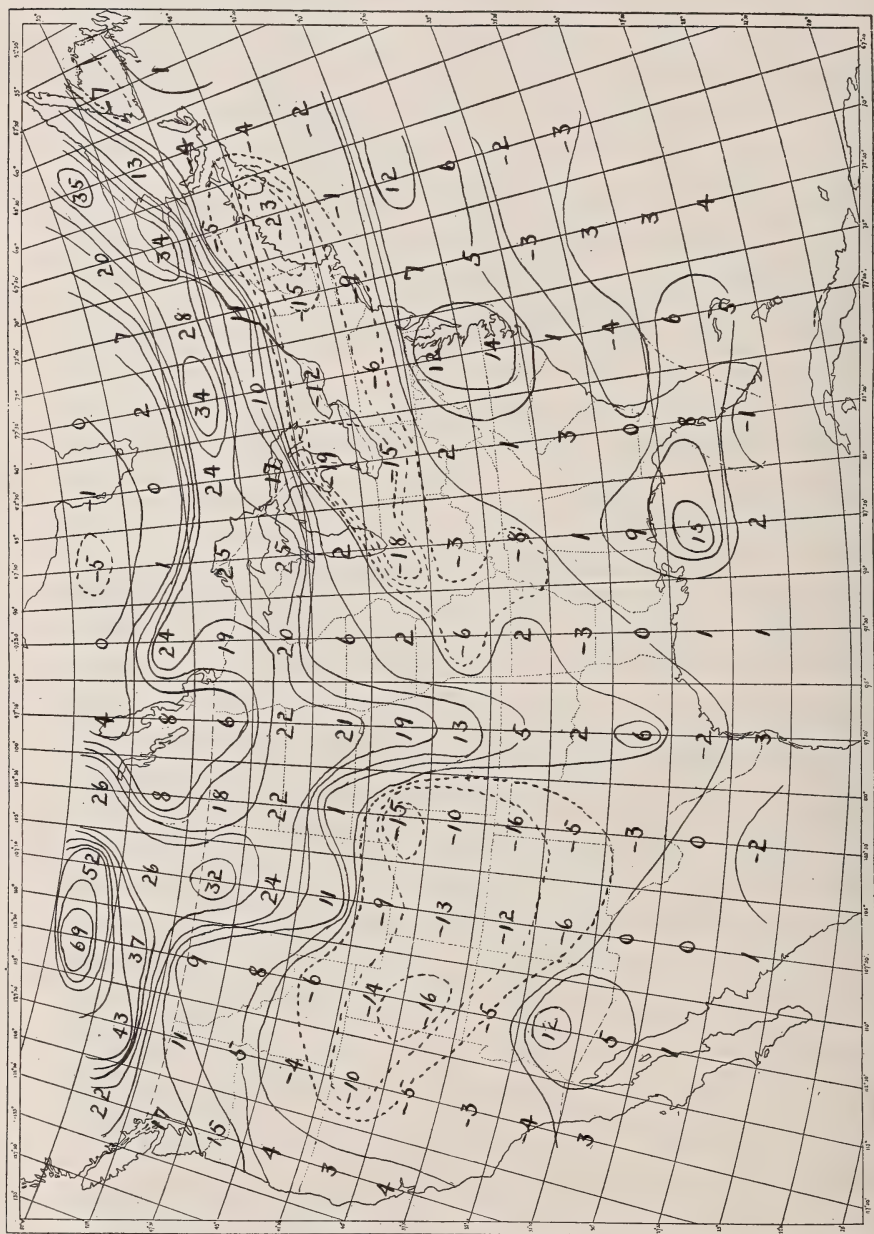


FIGURE 5.—Storminess during the Sun-spot Maximum of 1892-1894 compared with that of the Sun-spot Maximum of 1888-1890.
(After Kullmer)

The figures without sign indicate more storms during the period of maximum spots than during the period of minimum spots. The minus sign indicates less storms at maximum than at minimum spots.

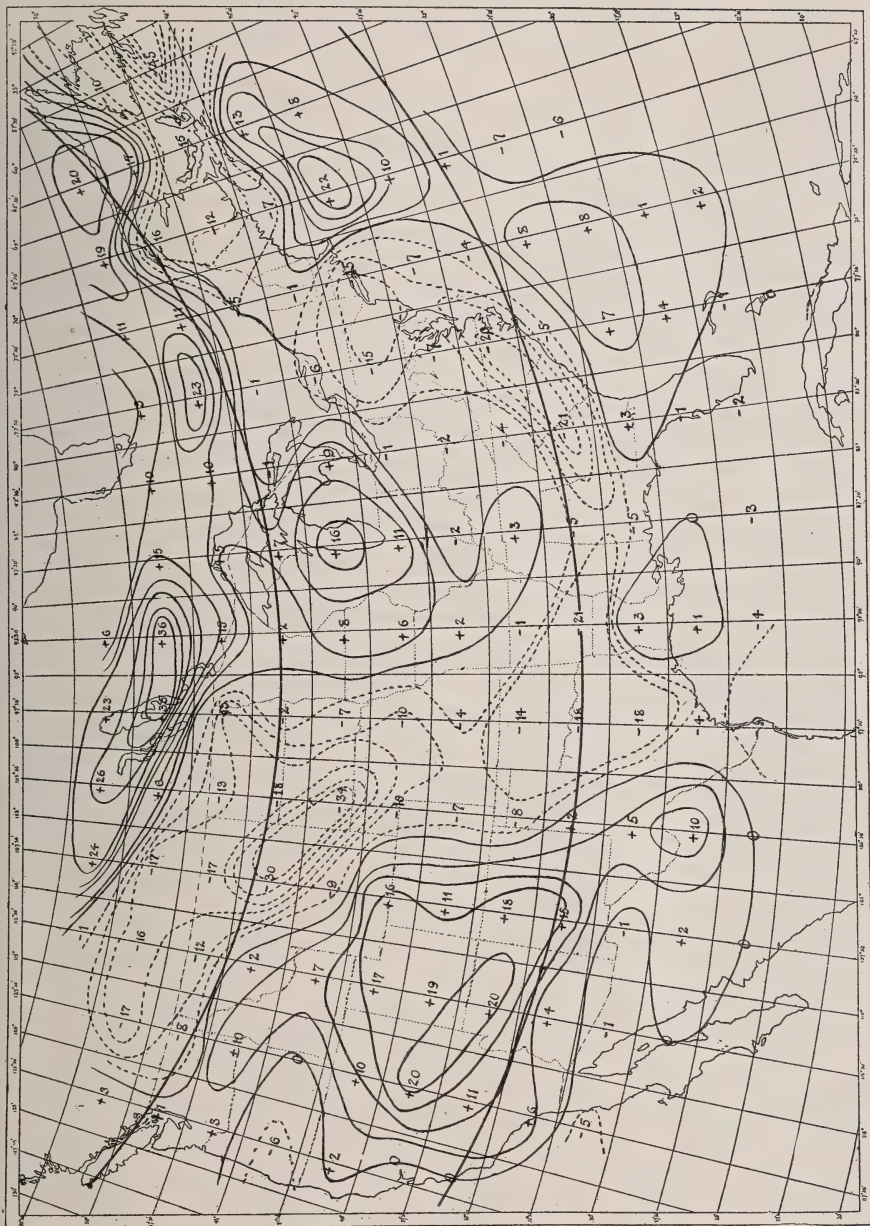


FIGURE 6.—Storminess during the Sun-spot Maximum of 1905-1907 compared with the Minimum of 1900-1902. (After Kullmer)

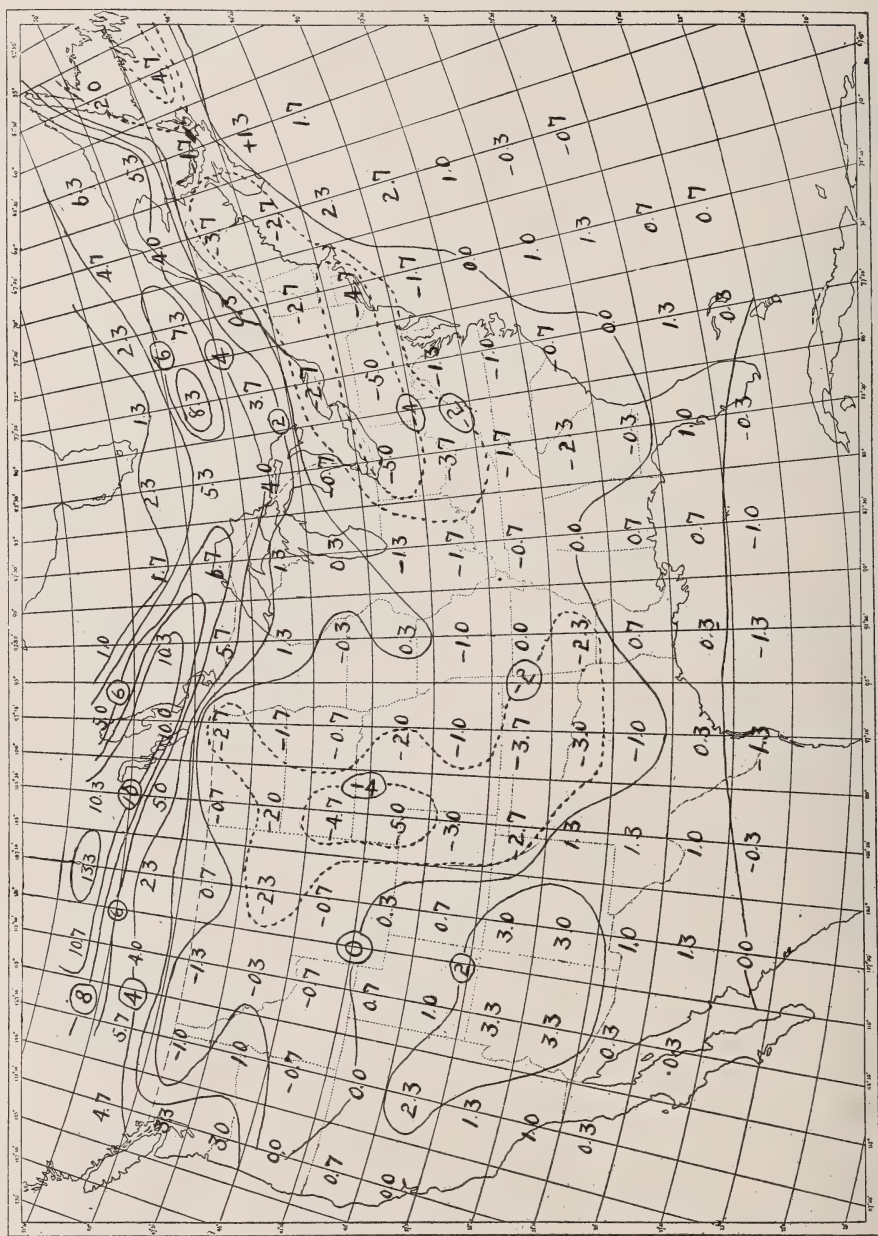


FIGURE 7.—Average Storminess of 9 Years of Sun-spot Maxima compared with 12 Years of Sun-spot Minima between 1877 and 1912. The minus sign indicates that the number of storms was less at times of sun-spot maxima than at times of sun-spot minima.

average number of storm tracks for a single year and not for groups of years, as in the other maps.

The most striking fact about these maps is that all of them show the same general features, and that although the location of the features varies somewhat from map to map, the variation is so slight that all the features of the individual maps reappear in a somewhat generalized form in the combination map of figure 7. The most noticeable feature is an arc-shaped area which lies along the southern border of Canada and is characterized by increased storminess during periods of many sun-spots. It begins in latitude 55° north on the west, drops down to about latitude 48° in the Great Lakes region, and then bends northward once more down the Saint Lawrence Valley. A second prominent feature is a peculiar projection which on each of the maps extends southward from the center of the area of excess. It almost divides into two parts the next prominent feature, which is a pronounced band of decreased storminess extending from Oregon through the central United States to Nova Scotia. South of this we have a second great area of increased storminess during times of many sun-spots. Although slightly broken in some of the maps of individual groups of years, it forms a continuous band in the combination map of figure 7. It is particularly well developed over the arid regions from California to western Texas and over the Atlantic Ocean. In one map, however, it becomes intensified in southern Texas. Finally, in the far south we find that in times of many sun-spots there is a slight suggestion of another little belt where storms decrease during times of many spots. This, however, is not well enough developed to be given much importance. In all these cases it should be understood that the words "increased" and "decreased" are used in a purely relative sense. In the northern belt of increased storminess the number of storms is always great, both at times of few sun-spots and of many. In the southern belt, on the contrary, the storminess is never very great, although at times of many spots it is distinctly greater than at times of few. I shall deal with this matter more fully later.

As a further test of the relation of storms and sun-spots Kullmer has constructed still another map, figure 8. In this case, instead of taking merely years of maximum and minimum sun-spot frequency, he has compared two complete sun-spot cycles with one another. Unfortunately, only two cycles are as yet available, but they are enough to provide an interesting test. One cycle consists of the 12 years from 1899 to 1900, inclusive, and the other of the 11 years from 1900 to 1911. In the first cycle the average sun-spot number was 38.8 and the average storminess 107.4 per cent. In the second the average sun-spot number was 33.3 and

the storminess 99.8 per cent. Years of few as well as many sun-spots are, of course, included in both cases. Nevertheless there is a difference between the two cycles, as may be seen in figure 8. Here, just as in the other cases, we see a belt of increased storminess at the north, with a southward projection in its center. The deficiency in the central portion of the United States is more marked than in the other maps and extends more distinctly into the Pacific Ocean. Yet, as in the other cases, it is most pronounced toward the east and the west and almost disappears in the center. Finally, in the south there is a well defined, although not very intense, belt of increased storminess at times of sun-spot maxima. The only feature of the other maps which does not appear is the most southerly belt of decreased storminess. A similar comparison of the cycle from 1878 to 1888 with the succeeding cycle, 1889 to 1900, shows the same general features for the area east of the 100th meridian, which is as far as data are available. Even the southern belt of deficiency is faintly apparent.

The resemblances of all these maps apparently lead to the conclusion that we are dealing with a phenomenon which repeats itself regularly with every repetition of the solar cycle. Not only does the number of storms seem to vary in harmony with the number of sun-spots, but also, and much more markedly, there is a pronounced shifting of the area of storminess. The shifting is so regular that we can not avoid the conclusion that Kullmer has discovered one of the important laws of nature. Other investigators, such as Bigelow,¹⁸ have noted that the location of storm tracks and the occurrence of cold waves have a relationship to sun-spots; but it has remained for Kullmer to put the matter into such form that we can definitely speak of the law of the shifting of storm tracks in harmony with changes in the intensity of solar activity. The meaning of Kullmer's law may be summed up briefly. The great area of excessive storminess in southern Canada means that when sun-spots are numerous the main storm belt shifts northward. This is the point on which Kullmer most strongly insists. I would add that at such times the main storm belt tends to split. The major portion moves northward, while a smaller, but by no means unimportant, portion shifts southward and oceanward. Thus the storminess of the center of the continent is less at times of many sun-spots than at times of few, while southern Canada and a large area in the south and over the ocean become more stormy. If this process went farther it would apparently result in two storm belts—a boreal belt of great severity and a subtropical belt of minor severity. It

¹⁸ Frank H. Bigelow: Studies on the circulation of the atmospheres of the sun and of the earth. Monthly Weather Review, 1904.

must be clearly understood, however, that during recent times the process has not gone far enough to produce belts which stand out unmistakably. How far the process usually goes will be shown on a later page.

In this connection Kullmer points out that Spoerer's law of the shifting of sun-spots in latitude may also apply to cyclonic storms. At the beginning of a new sun-spot cycle spots appear in about latitude 30° on either side of the solar equator. As the sun's activity increases, the location of new spots is farther and farther toward the equator. When the maximum intensity is reached, the average position is about 15° from the equator. Then as a cycle dies away the zone of chief activity falls to a latitude of 10° or less. Before this happens a new cycle begins in higher latitudes, and for a period of about three years there are two distinct belts, one waxing and the other waning. The double terrestrial belt at times of maximum sun-spots may be of similar origin. The matter is introduced here merely as a suggestion of one of the many interesting lines of research which are opened up by the study of storms.

Shifting of storms in the main storm belt.—In order to ascertain how closely the shifting of the storm belt coincides with solar phenomena, I have made an independent investigation of the area where there is the greatest change in storm frequency from times of maximum to minimum sun-spots. This area is inclosed within heavy meridians and parallels on the map (figure 3). In a limited area of this sort the number of storms depends almost wholly on the amount of shifting of the storm belt and only slightly on the actual change in total storminess for the whole country. As a first step, the 30 years for which accurate data are available have been divided into six groups of five years each, in accordance with the number of sun-spots, just as was done for the whole country on an earlier page. The results are given in Table 4, on page 502. The general conclusion is the same as for the continent; but the differences between the groups are far more marked, because we are dealing with a shift as well as with actual differences in the total storminess. Making allowances for the possible error in the group having a sun-spot number of 58.0, where the figure for 1905 and 1906 is 101.0, instead of 98.2 for the whole group, we see that in general the number of storms increases with the spottedness. The middle groups are none of them far from 100 per cent. The difference between the highest and lowest groups, however, which for the whole continent amounts to 15.8 per cent, has here increased to 46.9 per cent. The excess of 46.9 per cent over 15.8 per cent represents the effect of the northward shifting of the main storm belt.

If we divide our period of 30 years into four groups instead of six, the relationships of sun-spots and storms becomes much clearer than with

a division into six groups. When this is done, the table appears as follows:

TABLE 5

	Per cent
7 years, with sun-spot numbers above 60 (average, 70.4) . . . storminess	114.1
8 years, with sun-spot numbers from 35 to 60 (average, 46.8) . storminess	101.6
7 years, with sun-spot numbers from 10 to 35 (average, 21.1) . storminess	99.3
8 years, with sun-spot numbers below 10 (average 5.7) storminess	85.4

The similarity between these figures and those for tropical hurricanes in Table 2, on page 494, is striking. It seems impossible to avoid the conclusion that the same phenomena are repeated on both the northern and southern borders of the region where cyclonic storms prevail. The maps which we have discussed above make it equally clear that in the intervening region there is a corresponding decrease of storminess.

Before leaving this subject let us take the area of maximum change of storminess—which is the area included within the heavy lines in figure 3, and which is also the area of maximum storm frequency—and compare it with the sun-spots year by year. In this comparison I shall include the early years from 1874 to 1882, as well as the later and more reliable years when the data cover the whole country. These earlier years are probably more or less closely comparable with one another, although the first years are less reliable than the later ones, and there is a slight break between 1882 and 1883. Moreover, as already implied, the years 1883 to 1885 may not be so reliable as those that follow. The results of the comparison are given in figure 9. The upper heavy line represents the variations in the number of storms in the American area of maximum storminess. From 1876 to 1891 a dotted line has been added, indicating the combined storminess of the American area and of a similar area in Europe, but the European area is less well defined than the American and the data are of less value. Confining our attention to the American curve, we see that for the seven years from 1874 to 1880, inclusive, the curve of storms agrees closely with that of sun-spots, which appears below it. Even the little maximum of 1877 appears in both curves. In 1881, however, the amount of storminess drops suddenly, although the number of sun-spots keeps on increasing. Then for four years the two curves again agree, for both approach a maximum in 1884 and begin to fall in 1885. The next year the storms again behave differently from the sun-spots, but this does not continue long, for in 1887 and 1888 both curves again decline. The following year the storms increase in number, while the sun-spots remain stationary. If the two sets of phenomena are really due to the same cause, the delay of the sun-spot curve may possibly be due to the fact that the atmosphere of the earth is much smaller and per-

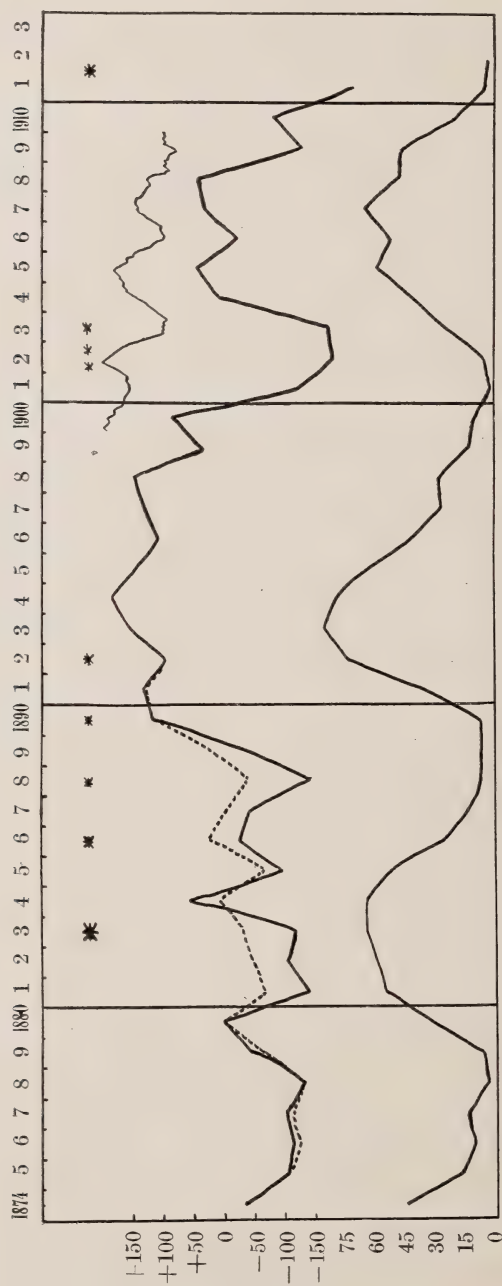


FIGURE 9.—*Storms (main upper curve) and Sun-spots (lower curve) in the main American Area of Storm-shifting, according to Kullmer's Law*
 Stars indicate important volcanic eruptions. The fine upper line shows the departures from the mean temperature at Arequipa, in Peru, according to Arctowski

haps more mobile than the lower portion of the sun's atmosphere where sun-spots apparently originate. Therefore, when the exciting cause begins to act, the earth may respond immediately, while a certain amount of time must elapse before the sun becomes sufficiently disturbed to show much evidence of it. This perhaps explains why in 1890 storminess has become highly pronounced, although the spots of the sun are only beginning to become active. The degree of importance to be attached to this explanation is not great, however, for in 1894 and 1908 the maxima of storms come a year after those of spots. The increase in storminess after the spots have passed their maxima is, to be sure, only slight, but it deserves notice. At present our knowledge is too scanty to enable us to determine the minor causes which induce the sun-spots and storms to act differently in certain cases.

To resume our analysis of the curves, in 1891 both rise, but the following year shows disagreement. Thereafter for 20 years a high degree of agreement is observed. It pertains not only to the major fluctuations, but to such little variations as the minor maxima of 1898 and 1900, both of which appear as irregularities in the sun-spot curve. In the last of the three sun-spot cycles the agreement is more striking than anywhere else. Each of the three irregularities in the upper curve is plainly apparent in the lower.

A test of the shifting of storm tracks by means of correlation coefficients with sun-spots.—The relationship shown in the two curves of figure 9 forms, so to speak, a concrete summary of the main fact of Kullmer's law of the shifting of storm tracks. It thus illustrates the most important single piece of evidence on which is based the hypothesis here under discussion. Therefore it should be tested most rigorously. The most severe mathematical test which can be applied to two such curves is that of correlation coefficients. It will be remembered that in computing these it is first necessary to find the amounts by which each of two phenomena during each of a series of years departs from the average for the entire series of years. From these values a standard mathematical process makes it possible to determine the exact degree of relationship. If the two phenomena are absolutely unconnected the coefficient is zero. If they are absolutely connected so that one never occurs without the other, and so that their relationship can be expressed by an invariable mathematical formula, the coefficient is 1. Such a relationship is like that of the rising of the sun to the rotation of the earth, or of the driving wheels of an engine, which can not turn except in harmony with the stroke of the piston. Other related phenomena, such as the amount of food which a man eats and the amount of work that he does, are expressed by coefficients

which can not possibly be as high as 1, nor can they possibly fall as low as zero. If the data used in the computations are free from perceptible error, a coefficient approaching 0.50 indicates a high degree of connection. The coefficients may have either a plus or a minus sign. The sign is positive when the maxima of one phenomenon are connected with the maxima of the other, while it is negative if the maxima of one are connected with the minima of the other.

In the case of the two curves of figure 9 the correlation coefficients have been computed in various ways, as shown in Table 6. The table shows the correlation coefficient between the number of storms in any given year and the sun-spot numbers of various years or combinations of years. For instance, the first line, "Storminess of a given year and sun-spots of the third year previous, $+0.074$," indicates that when the storms of a given year are compared with the number of sun-spots during the third year before that time, the correlation coefficient is only $+0.074$. So small a coefficient is unimportant. It indicates that there is no particular relation between the storms, say of 1914, and the sun-spots three years previously—that is, during 1911. The next line shows that when the storms are compared with the sun-spots of two years before—that is, when the storms of 1914, for example, are compared with the sun-spots of 1912—there is a connection, and if the number of sun-spots was on the increase in 1912 the number of storms is likely to be great in 1914. The next three lines show coefficients of $+0.41$, $+0.49$, and $+0.46$. This indicates a high agreement. It is noticeable here that there is more agreement between the storms of any given year and the sun-spots of the *succeeding* year than between the storms and the sun-spots of the *preceding* year. This is significant because it supports an idea which has already been suggested, namely, that the storms are not due directly to the spots, but to certain conditions of the sun, which cause an excitement of the sun's atmosphere manifesting itself in spots, and also of the earth's atmosphere manifesting itself in storms. The disturbance seems to produce its maximum effect on the earth slightly sooner than on the sun. The last three correlation coefficients show that when the storms of a given year are compared with the sun-spots not only of that year, but of that year combined with the year before or the year after, or with both, the relationship is higher than when individual years are considered. It reaches its maximum, $+0.535$, when the storms of a given year are compared with those of that same year, together with the succeeding year. From the mathematical point of view, this affords the strongest possible demonstration of a relationship between the two phenomena.

TABLE 6

Correlation Coefficients between Storminess in the Main Storm Track Area of North America for the 30 Years from 1883 to 1912 and Sun-spots during various Years and Combinations of Years

Storminess of a given year and sun-spots of the third year previous..	+0.074
Storminess of a given year and sun-spots of the second year previous.	+0.220
Storminess of a given year and sun-spots of the first year previous...	+0.409
Storminess of a given year and sun-spots of the same year.....	+0.486
Storminess of a given year and sun-spots of the first year later.....	+0.463
Storminess of a given year and sun-spots of the second year later....	+0.232
Storminess of a given year and sun-spots of the same year, together with preceding and succeeding years.....	+0.530
Storminess of a given year and sun-spots of the same year, together with preceding year.....	+0.465
Storminess of a given year and sun-spots of the same year, together with succeeding year.....	+0.535

Cyclonic storms and volcanic eruptions.—Turning back now directly to the curves of figure 9, we see that during the entire period of 38 years covered by both curves the only distinct disagreements are 1881, 1886, and 1892, to which we ought probably to add 1883. The cause of these may be found either in the volcanic eruptions or meteorological accidents, already discussed, or in some other cause as yet unknown. We can test them as to volcanic eruptions, but not in other respects. Such a test gives a negative result. Volcanoes, as we have seen, appear to have a direct influence on the earth's temperature. Therefore, if storms depend primarily on conditions of temperature acting through barometric pressure and winds, we ought to be able to trace the influence of volcanic eruptions in the storm curve. This does not seem to be possible, as may be seen in figure 9, where stars indicate eruptions according to the data of Humphreys given in figure 1. The eruption of Krakatoa, in 1883, falls two years after the most notable year of disagreement between sun-spots and storms. The eruption of Tarawera, in 1886, coincides with an anomalous increase in storminess; that of Bandai San, in 1888, corresponds with a decrease which is normal, if we assume that sun-spots and storms are really due to the same cause. The outburst of Bogoslof, in 1890, comes at a time when the storms increase in number, but it is noticeable that the increase is more than would be expected on the basis of solar relationship. The eruption of Awoe, in 1892, on the contrary, is accompanied by a decrease. The four remaining volcanic eruptions occur when the number of storms is small. It may be worth noting that 1903 is a somewhat abnormal year, for the number of storms remains lower than would be anticipated, yet the storminess increases somewhat and is thus in har-

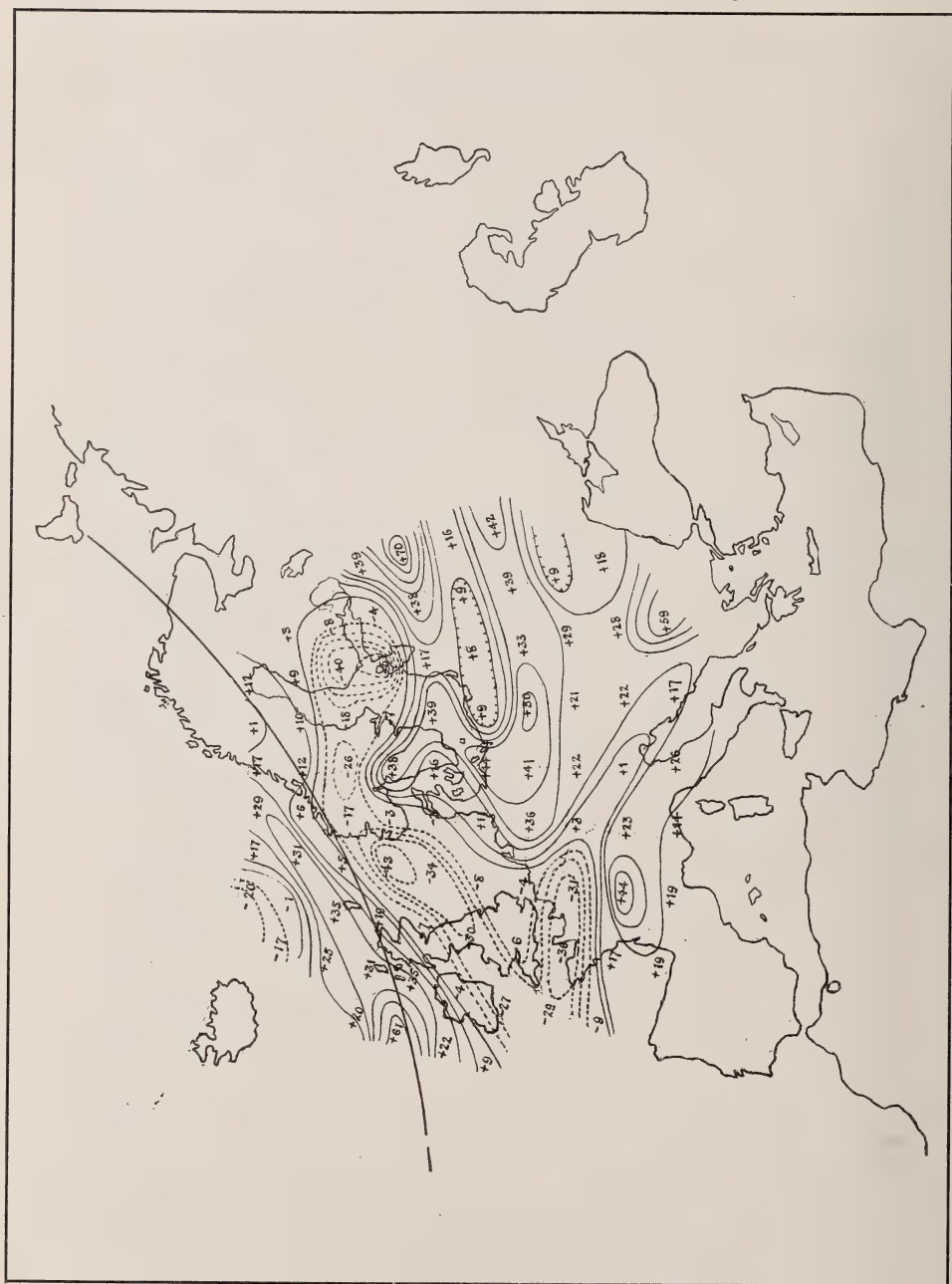


FIGURE 10.—Comparative Storminess of Europe during the Sun-spot Maximum of 1882-1884 and the Minimum of 1877-1879. (After Kullmer)

mony with the sun-spots. Taking the eruptions as a whole, it is hard to see that they have had any special influence. The only possible generalization seems to be that as a rule the volcanoes are active at times when the number of storms is somewhat lower than would be expected, but 1886 and 1890 are exceptions. The logical conclusion seems to be that while volcanic eruptions may have a temporary effect on the general temperature of the earth, the changes of temperature thus caused do not perceptibly influence cyclonic storms. This supports the idea that storms are not due primarily to conditions of temperature. It thus strengthens our previous conclusion that although volcanic eruptions may be of importance, they are nevertheless only a minor factor in causing climatic changes. It also strengthens the conclusion that storms are not due primarily to conditions of temperature. It does not, however, shed any light on the reason for the occasional disagreements between the curves of sun-spots and of storms. That problem must for the present be left unsolved.

Shifting of the storm track in Europe.—Having reached this conclusion, we must next ascertain whether the phenomena of Europe are similar to those of America. Because of the scarcity of data for European storm tracks and because of the lack of homogeneity in the 16 years for which records are available, we can not as yet determine whether the total storminess is greater in periods of many sun-spots than in periods of few. Fortunately, this does not prevent us from comparing the distribution of storms under different circumstances.¹⁹ In Europe only one period of maximum spots is available, the years 1882-1884, but there are two minimum periods, 1877-1879 and 1888-1890. Therefore each of these has been compared with the same maximum.

The results of this comparison are shown in figures 10, 11, and 12. The first two show the relative number of storms in periods of minimum sun-spots, 1877 to 1879 and 1888 to 1890, respectively, as compared with the intervening maximum of 1882 to 1884. The third diagram, figure 12, shows the other two combined. Figure 11 covers a much larger area than the other two maps, since the region where observations were included after 1882 was much larger than in the preceding period. In spite of certain places where there is a good deal of doubt as to the rela-

¹⁹ We can not compare the figures directly, as was done in America. By the use of percentages, however, we can obtain a fairly satisfactory result. The method is merely to find the average storminess for all squares during each three-year period of maximum or minimum spots, and then to call this average 100 per cent. On this basis the value of each square for each period is computed and the differences are determined. Provided that all parts of the country were mapped in the same way during a given period, the results are the same as if direct comparisons were instituted according to the method employed in America.

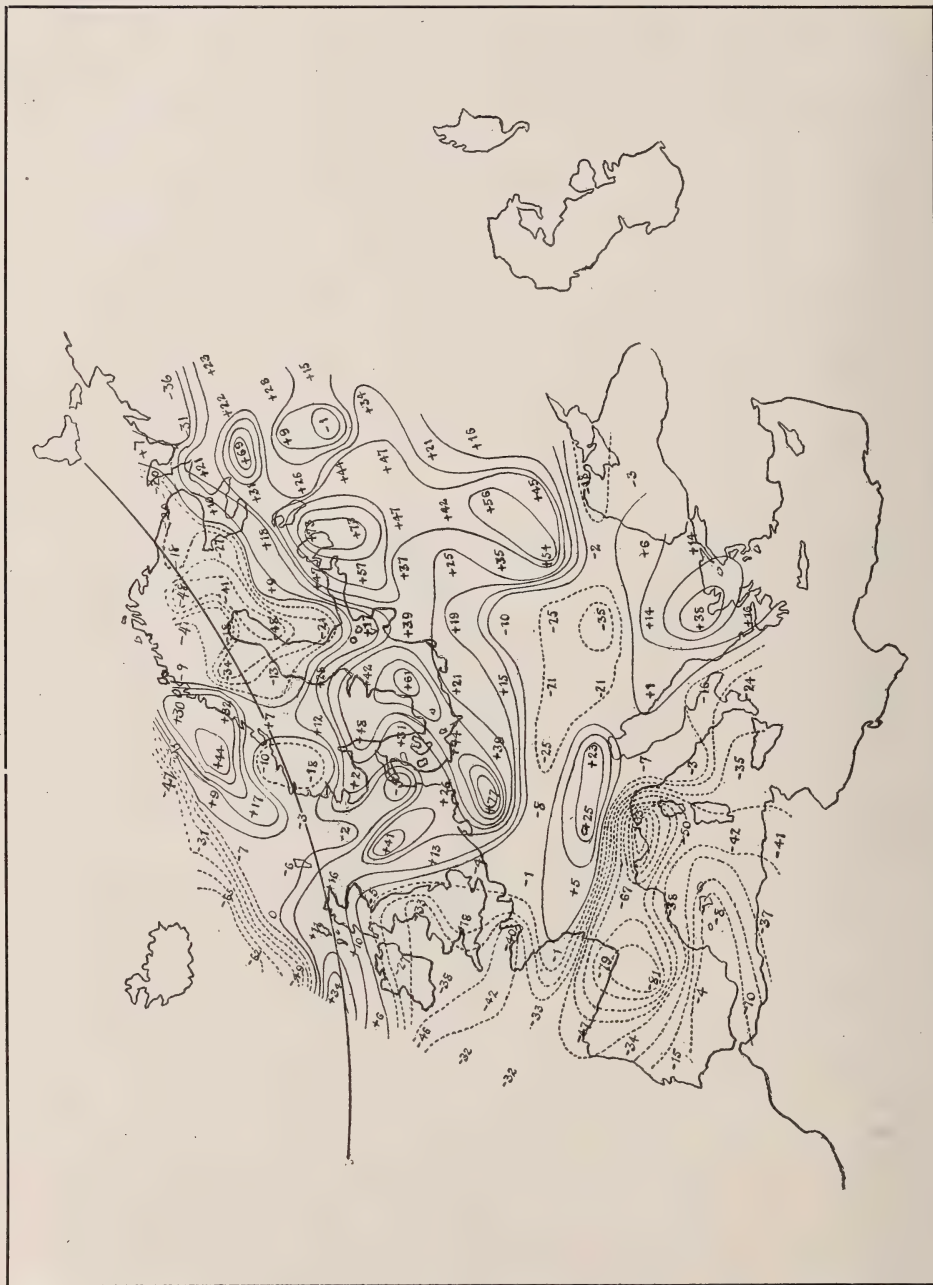


FIGURE 11.—Comparative Storminess of Europe during the Sun-spot Maximum of 1882-1884 and the Minimum of 1888-1890. (After Kullmer)

bility of the maps, the general features stand out quite strongly. In the first place, as to the unreliable parts, it is doubtful whether in figure 11 the areas of deficiency in the far northeast, northwest, and especially the southwest, should be so pronounced as they are. This feature probably arises from the fact that more abundant observations were available at the time of the sun-spot minimum of 1888-1890 than in the preceding maximum. Disregarding these features, however, we see that there is a distinctly belted character like that of the American maps. In the first place, each map shows a belt of deficiency in the North Atlantic Ocean near Iceland. Then follows a belt of excess occupying the oceanic area between Iceland and Scotland and extending over into Scotland and the northwestern part of Scandinavia. The next belt of deficiency begins in Ireland, covers southern and western England and northwestern France. Although broken in figure 11, it extends northeastward across the North Sea into Scandinavia, crosses the northern arm of the Baltic, and after another interruption becomes pronounced once more in Finland. The third belt, which is an area of great storminess during sun-spot maxima, begins in central France and extends northeastward into Russia. Its southwestern extremity, however, is more or less detached from the rest and seems to be on the point of disappearing in figure 11. Farther to the east an area of comparative deficiency in figure 10 and of actual deficiency in figure 11 lies over southwestern Russia and Hungary. Beyond it there is a third belt of increasing storminess lying over the Balkan Peninsula. Until more exact data are available it is not possible to place much reliance on the minor features of these maps. The division into belts running northeast and southwest, however, is unmistakable, and so, too, is the tendency for these belts to be broken in certain places, such as southern France, Hungary, and the region just north of the Alps. The phenomena are essentially the same as in America. There are at least two and possibly three main belts of excessive storminess and an equal number of belts of deficiency at times of numerous sun-spots. Local circumstances, such as seas and mountains, disturb the continuity of the belts, and this is perhaps the reason why they are less regular than in America. During periods when the sun-spots are few the belts tend to disappear and the storms are concentrated in the main continental area. The surrounding areas are characterized by diminished storminess.

This corresponds with the evidence of the trees at Eberswalde. The trees grow fast, it will be remembered, at times when the rainfall of the months from April to November is particularly abundant. Figures 10, 11, and 12 show that northern Germany is one of the areas where storms notably increase at periods of sun-spot maxima. This does not mean,

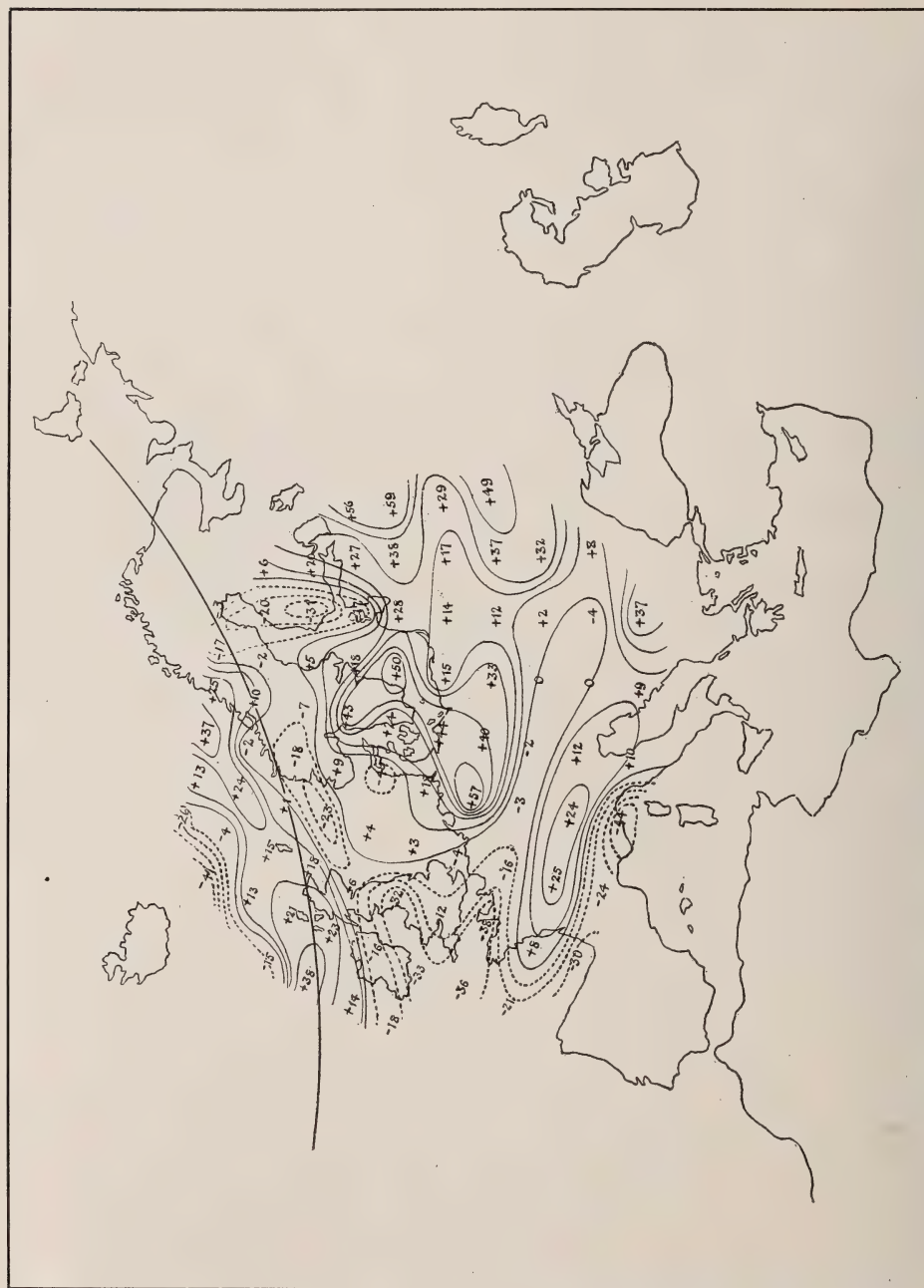


FIGURE 12.—Comparative Storminess of Europe during Periods of Maximum and Minimum Sun-spots
(Figures 10 and 11 combined)

however, that winter storms increase. Not only do the trees suggest that the winters have relatively few storms, but Kullmer's figures demonstrate it. If the average number of storms from December to March during the years 1877-1879 and 1888-1890, when the sun-spots were at a minimum, be taken as 100, the number during the intervening period of maximum spots, 1882-1884, is 81.8. If the summer storms from April to November are taken in the same way, the figures become respectively 100 and 160. In other words, at this particular time of maximum spots winter storms decreased somewhat in northern Germany, while summer storms increased greatly. The long curve of tree growth in figure 2 suggests that this happens regularly during each repetition of the sun-spot cycle. If this is true, it has an important bearing on what we shall soon say as to changes of climate in earlier times.

The "cyclonic" versus the "caloric" form of the solar hypothesis.—This brings us to the end of our consideration of modern climatic variations and their causes. In summing up the matter, we see first that the unassailable evidence of Newcomb, Köppen, Hann, and others proves that there is a close relationship between changes of temperature in tropical regions and changes in the sun-spot cycle. The work of Arctowski shows that in tropical regions and in the extratropical areas where the climate is under direct solar control, there are synchronous departures of the temperature from its mean value, and that these must be due to some widely acting cause, probably the sun. An amplification of Arctowski's work indicates that where we find discrepancies and apparent contradictions between the variations of temperature in different regions, they appear to be explicable as the result of the transportation of heat by currents of air, and to a much greater degree by currents of water. Other discrepancies appear to be due to the dust of volcanic eruptions, and probably there are still other causes which we have not yet discovered. Next we have seen that in spite of our conclusions as to the influence of the sun, the measured variations in the solar constant do not lead to the belief that such variations are the main cause of differences in terrestrial temperature. This leads to the consideration of other climatic phenomena which may be related to solar changes. We find that in tropical regions there is strong evidence that the number of cyclonic storms varies in direct harmony with the sun-spots. In northern Germany the growth of trees shows that when sun-spots are at a maximum the climate tends to become continental, with wet, stormy summers, relatively dry winters, and early springs. When sun-spots are few, on the contrary, oceanic conditions prevail and the contrast between summer and winter diminishes. The actual figures as to the number of storms support this conclusion.

In North America Kullmer's figures point to an increase in the total number of storms at times of maximum sun-spots, no matter in what way we investigate them. In both Europe and North America there seems to be an unmistakable shifting of the zone of storminess in response to changes in solar spots. Taking the evidence as a whole, we seem justified in saying that, in spite of previous conclusions to the contrary, we actually find as much agreement between climatic phenomena and sun-spots as would be expected on the assumption that variations in the sun are the main factor in producing variations in terrestrial climate. This, in brief, is the outline of what may be called the "cyclonic" solar hypothesis as distinguished from the old "caloric" solar hypothesis.

The reduction of terrestrial temperature by cyclonic storms.—Let us now return to a subject which has continually confronted us, but which it has not been possible properly to elucidate until the question of cyclonic storms had been discussed. One of the most important objections to the solar hypothesis is the disinclination of astronomers to believe that the mean temperature of the sun can have changed repeatedly to such an extent as to cause the observed climatic changes of the geological past. This view is supported by the fact that although the changes of climate now in progress show a close relationship with changes in sun-spots, they do not agree at all closely with changes in solar radiation as measured by the pyrheliometer. This raises the question of the effect which variations in the intensity of storminess may have on the temperature of the earth's surface. In answering this, as will shortly appear, we seem to be led to the conclusion that the temperature observed on the earth's surface can change in harmony with the sun-spots without demanding any change of temperature in the sun.

We have seen that in North America the amount of storminess may be as much as 15 per cent greater during years of the greatest sun-spot frequency than during those of least. In Europe equally great variations take place. For example, Kullmer's unpublished charts show that in 1885 the number of storm centers passing over a small area between Marseilles and Corsica was only 16. Four years later, in 1889, more than three times as many, 55 in all, passed over the same area. Part of the difference may be due to variations in the method of recording data, but much of it is real, for we find many similar occurrences elsewhere, both in Europe and America. Let us inquire into the necessary consequences of such changes, if they take place in such a way as to cause a general increase of storminess throughout the world. On the southern side of ordinary cyclonic storms in the northern hemisphere, no matter whether they are tropical hurricanes or the far more numerous storms of tem-

perate regions, air is drawn in from warm southerly latitudes. On the opposite side air is drawn in from relatively cold regions, especially in the main storm belt. In the center of the area of low barometric pressure, which is the fundamental feature of a cyclonic storm, the cold, heavy air from the poleward side flows under the warm, light air from the equatorward side. Thus, in the center, where there is a strong tendency for the air to rise because of the surrounding high pressure, it is the warmer air which rises. The rising air is carried far aloft. As it reaches higher altitudes, where the atmospheric pressure is less, it expands little by little and grows cool, according to the usual adiabatic laws. At the same time it grows cool by radiation, but this last process is much slower than the adiabatic cooling. Accordingly, air which is unusually warm when it leaves the earth's surface is still relatively warm when it reaches high altitudes. Manifestly such air carries heat away from the earth's surface. Having once reached a high altitude, it stays there a long time, for there are no rapid downward movements of the atmosphere at all comparable to the strong upward currents in the centers of cyclonic storms. During this period it grows cool by radiation, and much of the heat thus sent out is a complete loss, so far as the earth's surface is concerned.

During periods of many sun-spots the increase in the total intensity of the earth's storminess must cause a corresponding increase in the amount of air carried from low to high altitudes. The average rate of movement also increases in all probability, for the storms are likely to be more severe. When the amount of warm air that goes upward increases, and still more if it rises at a more rapid rate than formerly, it is evident that the amount of heat which is carried away from the earth's surface and is dissipated in the upper air must increase to a corresponding degree. As the air which thus rises is derived from regions to the equatorward of the storms, there would naturally be a distinct tendency to lower the temperature of the entire equatorial and subtropical area between the storm belts of the two hemispheres. Apparently the fact that at times of maximum sun-spots the storms tend to increase not only in a boreal, but a subtropical belt nearer to the equator than the present storm belt, increases the extent to which the equatorial regions are cooled by the draining away of their warmer air. Such a process of cooling the regions to the equatorward of the storm belt must apparently occur whenever the number of storms increases, no matter whether the amount of heat received from the sun changes or remains constant. In the storm belt a similar, but less noticeable, effect seems to be produced. More air than formerly is drawn in from the south, but more also comes from the north, and the two perhaps balance one another. The warm air, however, rises

much more than the cold air, and hence the total result must probably be to lower the temperature.

In polar regions the effect would be different. Recent explorations have established the fact that Antarctica and the great ice-cap of Greenland are regions of high pressure, and hence of descending air. The temperature of this air depends on the degree to which the air which has ascended in other places has had time to give off its heat before it begins to descend. It seems probable that when a given body of warm air rises in equatorial or temperate regions it stays aloft so long that when a portion of it finally descends in the midst of a polar area of high pressure it has lost as much heat as it can by radiation—that is, its temperature will be almost the same, no matter how warm it may have been when it rose. In that case the temperature of polar regions will suffer little change except in so far as there is a variation in the amount of heat received from the sun.

In view of the conditions here described, it appears as if changes in the storminess of the earth must cause changes in the mean temperature of the atmosphere at low levels, even without any change in the amount of heat received from the sun. The variations would take place in accordance with the phenomena which we actually observe and which have been tabulated by Köppen and others.

A possible magnetic or electric cause of cyclonic storms.—The verity of the conclusion just reached depends in part on the cause which future investigation may assign to cyclonic storms. We have seen that such storms seem to be directly connected with changes in the sun. We have also seen that certain phenomena, such as the apparent absence of any effect of volcanic eruptions on storminess, seem to imply that the location and intensity of storms is not due primarily to temperature alone. Kullmer has advanced some interesting reasons for suspecting some connection between storms and terrestrial magnetism. He points out that there are three centers of storminess, corresponding to the three magnetic poles. In the southern hemisphere there is only one magnetic pole. The cyclonic storms of that region circle around it in about latitude 60° south.²⁰ Their average path is not concentric with the pole of rotation, but with the magnetic pole. In the northern hemisphere the main magnetic pole lies in the northeastern part of North America, approximately in latitude 70° north and longitude 97° west. Corresponding to this we have the main stormy area of the world. It extends from the western

²⁰ See W. J. S. Lockyer: *Southern Hemisphere. Surface air circulation.* London, 1910. Also *National Antarctic Expedition, 1901-1904: Meteorology, Part II, comprising daily synchronous charts, 1st October, 1901, to 31st March, 1904.* London, Royal Society, 1913.

part of America, in about latitude 50° , across that continent to Europe and as far as the confines of Asia, where it gradually dies out. Here, just as in the southern hemisphere, the average path of the storm does not follow an arc concentric with the pole of rotation, but one much more nearly concentric with the magnetic pole. Finally, in Siberia, there is a minor magnetic pole. Corresponding to this there is a third stormy area which centers in Japan. Another fact which Kullmer points out as perhaps of importance in this connection is that in the Atlantic Ocean the lines of equal total intensity of magnetic force follow the same direction as the main storm tracks. The relation between the location of storms and the magnetic pole is brought out in most of the storm maps. Heavy solid lines have been drawn with the magnetic pole as a center. In North America the more northern line is drawn at a distance of approximately 25° from the magnetic pole. It does not run exactly parallel to the belt of maximum storminess or to the belt where storminess increases most rapidly during times of sun-spot maximum. Nevertheless there is a certain degree of correspondence. In figure 6 a southern line has been drawn about 38° from the magnetic pole. It does not agree with the southern storm belt to anything like so great a degree as does the other line with the northern storm belt, perhaps because the central protuberance of the northern belt pushes the storms unduly far to the south. Its continuation, however, is the more northerly line in the European maps. This, as may be seen in figure 4, lies not far from the main northern area of abundant storms.

How significant this possible agreement of magnetic and cyclonic phenomena may be can not yet be determined, but it is certainly worth investigating. The earth's magnetic field is closely connected with that of the sun. It is well known that among all the phenomena of the earth magnetism is the one which shows the most unequivocal connection with the solar changes which manifest themselves as sun-spots, protuberances, and other variations in the solar atmosphere. Hence, if cyclonic storms are in part a magnetic phenomenon, we should expect to find that they vary in harmony with the spots of the sun. Such variations would probably be also in harmony with changes in the amount of solar radiation, but they would not be due to it primarily, and might be of considerable magnitude when the temperature changes were slight. Although physicists are slow to believe that solar temperature can change rapidly, they all agree that electrical and magnetic changes may take place with great speed. These considerations are highly speculative and they are not essential to our main conclusions. They are of value, however, as suggesting some of the lines along which investigation may prove fruitful.

THE CLIMATE OF HISTORIC TIMES

GENERAL DISCUSSION

Having completed our survey of present climatic conditions, we are prepared to consider the climate of the past. The first period to claim attention is the few thousand years covered by written history. Strangely enough, the conditions during this time are known with less accuracy than are those of geological periods hundreds of times more remote. Yet if pronounced changes have occurred since the days of the ancient Babylonians and since the last of the post-Glacial stages, they are of great importance not only because of their possible historic effects, but because they bridge the gap between the little variations of climate which are observable during a single lifetime and the great changes known as Glacial epochs. Only by bridging the gap can we determine whether there is any genetic relation between the great changes and the small. A full discussion of the climate of historic times is not here advisable, for it has been considered in detail in numerous other publications. Our most profitable course would seem to be to consider first the general trend of opinion and then to take up the chief objections to each of the main hypotheses.

THE TREND OF OPINION AS TO THE CLIMATE OF THE PAST

In the hot debate over this problem during the last decade or two the ideas of geographers seem to be going through much the same metamorphosis as have those of geologists in regard to the climate of times far antecedent to the historic period. It is scarcely necessary to remind geologists of the way in which opinion has changed in regard to the climate of geological times. An admirable summary of the subject may be found in Schuchert's paper on "Climates of Geologic Times," which forms the concluding part of "The Climatic Factor," publication 192 of the Carnegie Institution of Washington. As every geologist well knows, at the dawn of geology people believed in climatic uniformity—that is, it was supposed that since the completion of an original creative act there had been no important changes. This view quickly disappeared and was superseded by the hypothesis of progressive cooling and drying, an hypothesis which had much to do with the development of the nebular hypothesis, and which has in turn been greatly strengthened by that hypothesis. The discovery of evidence of wide-spread continental glaciation, however, necessitated a modification of this view, and succeeding years have brought to light a constantly increasing number of glacial, or at least cool, periods distributed throughout almost the whole of geological

time. Moreover, each year, almost, brings new evidence of the great complexity of Glacial periods, epochs, and stages. Thus, for many decades, geologists have more and more been led to believe that the climate of the past has been highly unstable, and that its changes have been of all degrees of intensity.

PROGRESSIVE DESICCATION DURING HISTORIC TIMES

Geographers are now debating the problem of the reality of historic changes of climate in the same way in which geologists debated as to the reality of Glacial epochs and stages. Several hypotheses present themselves. In the first place, the hypothesis of progressive desiccation has been widely advocated. In many of the drier portions of the world, especially between 30° and 40° from the equator, and preeminently in western and central Asia and in the southwestern United States, almost innumerable facts seem to indicate that two or three thousand years ago the climate was distinctly moister than at present. The evidence includes old lake strands, the traces of desiccated springs, roads in places now too dry for caravans, other roads which make detours around dry lake beds where no lakes now exist, and fragments of dead forests extending over hundreds of square miles where trees can not now grow for lack of water. Still stronger evidence is furnished by ancient ruins, hundreds of which are located in places which are now so dry that only the merest fraction of the former inhabitants could find water. The ruins of Palmyra, in the Syrian Desert, show that it must once have been a city like modern Damascus, with one or two hundred thousand inhabitants, but its water supply now suffices for only one or two thousand. All attempts to increase the water supply have had only a slight effect and the water is notoriously sulphurous, whereas in the former days, when it was abundant, it was renowned for its excellence. Hundreds of pages might be devoted to describing similar ruins. Some of them are even more remarkable for their dryness than is Niya, a site in the Tarim Desert of Chinese Turkestan. Yet there the evidence of desiccation within 2,000 years is so strong that even so careful and conservative a man as Hann,²¹ pronounces it "überzeugend," although in other regions he does not feel that the matter has yet been settled. In all the discussions of the matter, so far as I am aware, no opponent of the hypothesis of climatic changes has ever even attempted to show by careful statistical analysis that the ancient water supply of these ruins was no greater than that of the present. The most that has been done is to suggest that there *may* have been sources of water which are now unknown. Of course, this might be true in a

²¹ J. Hann: *Klimatologie*, vol. 1, 1908, p. 352.

single instance, but it could scarcely be the case in many hundreds or thousands of ruins.

The arguments in favor of a change of climate during the last two thousand years seem too strong to be ignored. Their very strength, however, seems to have been a source of error. A large number of people, among whom I plead guilty of having been included during the earlier days of my geographical work, have jumped to the conclusion that the change which appears to have occurred in certain regions occurred everywhere, and that it consisted of a gradual desiccation.

CLIMATIC UNIFORMITY DURING HISTORIC TIMES

Other observers, quite as careful as those who believe in progressive desiccation, point to evidences of aridity in past times in the very regions where the others find proof of moisture. Lakes such as the Caspian Sea fell to such a low level that parts of their present floors were exposed and were used as sites for buildings whose ruins are still extant. Elsewhere, for instance in the Tian Shan Mountains, irrigation ditches are found in places where irrigation never seems to be necessary at present. In Syria and North Africa during the early centuries of the Christian era the Romans showed unparalleled activity in building great aqueducts and in watering land which then apparently needed water as much as it does today. Evidence of this sort is abundant and is as convincing as is the evidence of moister conditions in the past. It is admirably set forth, for example, in the comprehensive and ably written monograph of Leiter on the climate of North Africa.²² The evidence cited there and elsewhere has led many authors strongly to advocate the hypothesis of climatic uniformity. They have done exactly as have the advocates of progressive change, and have extended their conclusions over the whole world and over the whole of historic times.

CLIMATIC PULSATIONS DURING HISTORIC TIMES

The hypotheses of climatic uniformity and of progressive change both seem to be based on reliable evidence. They are diametrically opposed to one another, but this is apparently because the various lines of evidence have not been grouped according to their dates. When this is done, it appears that evidence of moist conditions is found during certain periods; for instance, four or five hundred years before Christ, at the time of Christ, and 1000 A. D. The other kind of evidence, on the contrary, culminates at other epochs, such as about 1200 B. C. and in the seventh and

²² H. Leiter: Die Frage der Klimaänderung während geschichtlicher Zeit in Nordafrika. Abhandl. K. K. Geographischen Gesellschaft. Wien, 1909, p. 143.

thirteenth centuries after Christ. It is also found during the interval from the culmination of a moist epoch to the culmination of a dry one, for at such times conditions would be growing drier and the people would be under stress. This was seemingly the case during the period from the second to the fourth centuries of our era. North Africa and Syria may have been moister than at present; but they were gradually becoming drier, and the natural effect on a vigorous, competent people like the Romans was to cause them to construct all manner of engineering works to provide the necessary water.

The considerations which have just been set forth have led to a third hypothesis, that of pulsatory climatic changes. According to this, the earth's climate is not stable, nor does it change uniformly in one direction. It appears to fluctuate back and forth not only in the little waves which we see from year to year or decade to decade, but in much larger ones, which take hundreds of years or even a thousand. These in turn seem to merge into and be imposed on the greater waves which form Glacial stages, Glacial epochs, and Glacial periods. At the present time there seems to be no way of determining whether the general tendency is toward aridity or toward glaciation. The seventh century of our era was apparently the driest time during the historic period—distinctly drier than the present—but the thirteenth century was almost equally dry, and the twelfth or thirteenth before Christ may have been very dry.

TREES AS A CLIMATIC YARDSTICK

The best test of an hypothesis is actual measurements. In the case of the pulsatory hypothesis we are fortunately able to apply this test. The growth of vegetation depends on many factors—such as soil, exposure, wind, sun, temperature, rain, and so forth. In the case of any individual tree, however, the variations from year to year depend largely on climate. The most critical factor for the great majority of plants is the amount of moisture during the few months of most rapid growth.²³ In the case of trees, the work of Douglass²⁴ and others has shown the thickness of the annual rings affords a reliable indication of the amount of moisture available during the period of growth. This is especially true when the growth of several years is taken as the unit and is compared with the growth of

²³ A most careful and convincing study of this problem is embodied in an article by J. W. Smith: *The effects of weather upon the yield of corn*. *Monthly Weather Review*, vol. 42, 1914, pp. 78-92. On the basis of the yield of corn in Ohio for 60 years and in other States for shorter periods, he shows that the rainfall of July has almost as much influence on the crop as has the rainfall of all other months combined.

²⁴ See chapter by A. E. Douglass in "The Climatic Factor"; also article by M. N. Stewart: "The Relation of Precipitation to Tree Growth," in *The Monthly Weather Review*, vol. 41, 1913.

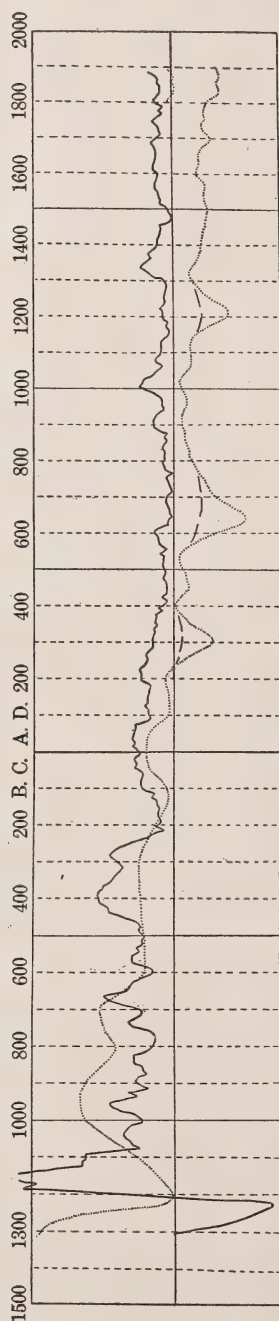


FIGURE 13.—Changes of Climate in California (solid line) and in western and central Asia (dotted line)

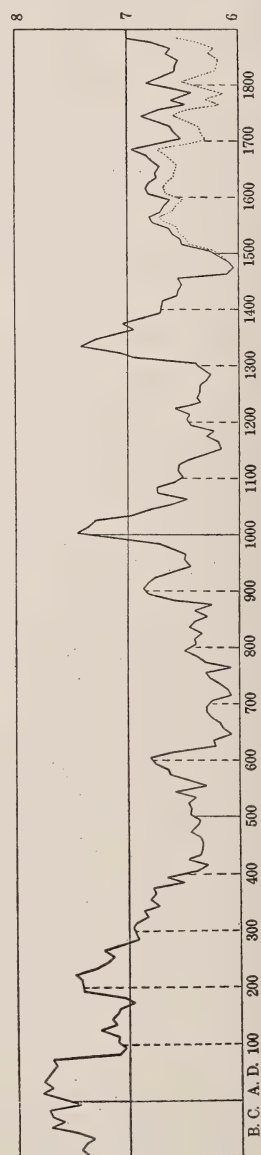


FIGURE 14.—Changes in California Climate for 2,000 Years, as measured by Growth of Sequoia Trees

a similar number of years before or after. Where a long series of years is used, it is necessary to make corrections to eliminate the effects of age, but this can be done by mathematical methods of considerable accuracy. It is difficult to determine whether the climate at the beginning and end of a tree's life was the same, but it is easily possible to determine whether there have been pulsations while the tree was making its growth. If a large number of trees from various parts of a given district all formed thick rings at a certain period and then formed thin ones for a hundred years, after which the rings again become thick, we seem to be safe in concluding that the trees have lived through a long dry period. The full reasons for this belief and details as to the methods of estimating climate from tree growth are given in "The Climatic Factor."

A brief summary of the results set forth in that volume is as follows: During the years 1911 and 1912, under the auspices of the Carnegie Institution of Washington, I measured the thickness of the rings of growth on the stumps of about 450 Sequoia trees in California. These trees varied in age from 250 to nearly 3,250 years. The great majority were over 1,000 years of age, 79 were over 2,000, and 3 over 3,000. Even where only a few trees are available the record is surprisingly reliable except where occasional accidents occur. Where the number approximates 100, accidental variations are largely eliminated and we may accept the record with considerable confidence. Accordingly, we may say that in California we have a fairly accurate record of the climate for 2,000 years and an approximate record for 1,000 years more. The final results of the measurements of the California trees are shown in figure 13, where the climatic variations for 3,000 years in California are indicated by the solid lines. The high parts of the line indicate rainy conditions, the low parts dry. An examination of this curve shows that during 3,000 years there have apparently been climatic variations more important than any which have taken place during the past century. In order to bring out the details more clearly, the more reliable part of the California curve, from 100 B. C. to the present time, has been reproduced in figure 14. This is identical with the corresponding part of figure 13 except that the vertical scale is three times as great.

In addition to the solid line of figure 13 there is a dotted line. This indicates the approximate climatic fluctuations of central and western Asia as I had inferred them before doing any work on this subject in America.²⁵ It is avowedly imperfect, especially in the earlier portions. Before the time of Christ information is so scanty that in some cases there are gaps of two or three centuries where no data are yet available.

²⁵ The curve is taken from "Palestine and its Transformation," pp. 327 and 403.

In spite of this, however, if the earlier, less reliable portions of the curves are omitted, the main features of the Asiatic curve agree in general with those of the California curve. Both curves seem to point to the conclusion that during the past two or three thousand years the climate of these two far removed portions of the world has been subject to approximately the same kind of climatic pulsations. The agreement of two such diverse lines of evidence is one of the strongest reasons for accepting the pulsatory hypothesis.

*CLIMATIC PULSATIONS ACCORDING TO CRITICS OF THE HYPOTHESIS OF
PROGRESSIVE DESICCATION*

Another reason for accepting it is found in the attitude of authors who support the hypothesis of climatic uniformity. As examples of this I shall take four who have written for the express purpose of controverting the views which I have expressed in "Explorations in Turkestan," "The Pulse of Asia," and "Palestine and its Transformation." Their arguments, however, are not directed against the idea of pulsatory changes, but against the idea that the climate of western and central Asia two thousand years ago was moister than at present. These four authors—Hedin, Gregory, Berg, and Herbertte—state distinctly their acceptance of the modern geological conclusion that since the Glacial period there have been climatic pulsations of the type known as post-Glacial stages. They hold, however, that by the beginning of the Bronze Age, say 1500 or 2000 B. C., these pulsations had come to an end. From that time onward for 3,000 or 4,000 years they state that the climate has been uniform. Nevertheless they all qualify this by admitting that during the past 1,000 years, more or less, there have been pulsations of greater magnitude than those which can be observed during the life of a single individual. For instance, the Swedish traveler Hedin²⁶ speaks of lakes Manasarowar and Rakas-tal, in southwestern Tibet, as forming admirable rain gauges. Both are without outlet most of the time. Manasarowar, however, overflows at fairly frequent intervals, perhaps in accordance with the Brückner cycle, and sends a stream to Rakas-tal. This lower lake overflows much more rarely and only in times of unusually marked precipitation. Hence its occasional periods of overflow at intervals of a few hundred years are taken by Hedin to indicate climatic pulsations having this duration. Hedin²⁷ also says that "the fact that the Caspian Sea was much lower 750 years ago than it is now . . . proves more clearly than anything else that the desiccation of the climate of central Asia and of the lakes by no means follows a regular curve." Elsewhere he says that

²⁶ Sven Hedin : *Trans-Himalaya*, vol. 3, p. 234 ; see also p. 288.

²⁷ Sven Hedin : *Overland to India*, vol. 2, p. 209.

"oscillations between dry and moist climates have succeeded one another all over western Asia. The opposite would be both unnatural and physically unaccountable."

The Russian geographer, Berg,²⁸ speaks in much the same way. He states that "during the 13th and 15th centuries and part of the 16th in western Asia and eastern Europe some increase in the precipitation was noticed. For instance, during this time the Amu Dariya sent a branch to the Caspian Sea through the Uzboi. . . . There is nothing to assure us that in the future such an abundance of water may not repeat itself."

Herbette,²⁹ a French geographer, expresses practically the same opinion.

In discussing the curve of the fluctuations of the Caspian Sea, which I have published in "The Pulse of Asia" (page 349), he objects strongly to the earlier portions before the low stand in the fifth, sixth, and seventh centuries of our era. I may add parenthetically that later work has led me to modify these earlier portions, although not to the extent advocated by Herbette. From the fifth century onward, however, he seems to accept the curve as reliable, for he says that "the rest of the curve indicates only that in the Middle Ages there were fluctuations of the level of the Caspian Sea more accentuated than those of our day."

Finally, the English geographer Gregory, the last of our four authors, admits the desiccation of Asia, and is also convinced that in northwestern Europe the climate has become more oceanic during the last few centuries. He says³⁰ that "both the summers and winters are now more moderate (than in the time of Tycho Brahe, whose observations cover the period from 1582 to 1597), while the temperatures of spring and autumn are unchanged." In Roumania³¹ he holds that the climate is now more moist than formerly. It thus appears that although the four authors here cited are among the strongest opponents of the hypothesis of a gradual drying up of the earth, and although they all expressly state their belief that there has been no pronounced change of climate during historic times, they all admit the main elements of the pulsatory hypothesis. From the height of the last Glacial epoch to about 1500 or 2000 B. C. they agree in believing that pronounced pulsations took place. They also agree that during the last thousand years, more or less, there have been

²⁸ L. Berg: Variations of climate in historic times (On Russian). Zemleveduié, Moscow, 1911, p. 75.

²⁹ Francois Herbette: Le Problem du Dessechement de l'Asie Centrale. Annales de Geographie, vol. 23, 1914, pp. 1-30.

³⁰ J. W. Gregory: Is the earth drying up? Geog. Jour., vol. 43, 1914, pp. 148-172 and 293-318.

³¹ See G. Murgoci: The climate in Roumania and vicinity in the late Quaternary times. Postglaziale Klima veränderungen. Stockholm, 1910.

minor pulsations of one kind or another which are larger than those observed during a single lifetime or than those recorded since accurate observations were possible on a large scale. In other words, a careful study of the available facts has led these four authors to reject the hypothesis of progressive changes and to accept the hypothesis of large pulsatory changes previous to about 2000 B. C. and of small changes of the same kind since about 600 A. D. The only point where their view differs radically from the one advocated in this paper is in the interpretation of the evidence from 2000 B. C. to the early part of the Christian era. Were the pulsations of that time of the small type which seems to have prevailed during the last 1,500 years, or were they intermediate between those and the larger ones of post-Glacial stages?

OBJECTIONS TO THE HYPOTHESIS OF CLIMATIC CHANGES

Ancient droughts and famines.—Reasons for believing that the pulsations were intermediate rather than small have already been mentioned in our discussion of ruins and allied phenomena. It will now be advisable to consider the objections to this view. Only three of chief importance can be taken up. The first is the unquestionable fact that droughts and famines have occurred at periods which seem on other evidence to have been moister than the present time. This argument has been much used, but it seems to have little force. If the rainfall of a given region averages 30 inches and varies from 15 to 45, a famine will ensue if the rainfall drops for a few years to the lower limit and does not rise much above 20 for a few years. If the climate of the place changes during the course of centuries, so that the rainfall averages only 20 inches, and ranges from 7 to 35, famine will again ensue if the rainfall remains near 10 inches for a few years. The ravages of the first famine might be as bad as those of the second. They might even be worse, because when the rainfall is larger the number of people is likely to be greater and the distress due to scarcity of food would affect a larger number of people. Hence historic records of famines and droughts do not indicate that the climate was either drier or moister than at present. They merely show that at the time in question the climate was drier than the normal for that particular period.

The existence of deserts in ancient times—Alexander's march.—The march of Alexander from India to Mesopotamia illustrates a second type of objection which is often urged against the idea that the climate of that time may have been moister than that of the present. Hedin gives an excellent presentation of the case in the second volume of his "Overland to India." He shows conclusively that Alexander's army suffered terribly

from lack of water and provisions. Various other authors, among whom I have been one, have taken the opposite view, and have maintained that the large size of Alexander's army, and especially the presence of elephants, prove that the march would have been impossible under present climatic conditions. As a matter of fact, it is extremely doubtful whether any reliable conclusion can be drawn from this one incident when taken by itself. We do not know whether Alexander's march took place during an especially dry or an especially wet year. In a desert region like Makran, in southern Persia and Beluchistan, where the greatest difficulties occurred, the rainfall varies greatly from year to year. We have no records from Makran, but the conditions there are closely similar to those of southern Arizona and New Mexico. In 1885 and 1905 the rainfall for five stations in that region was as follows:

	1885.	1905.	Mean rainfall during period since observations began.
Yuma, Arizona.....	2.72	11.41	3.13
Phoenix, Arizona.....	3.77	19.73	7.27
Tucson, Arizona.....	5.26	24.17	11.66
Lordsburg, New Mexico.....	3.99	19.50	8.62
El Paso, Texas (on New Mexico border) ..	7.31	17.80	9.06
Average.....	4.61	18.52	7.95

These stations are distributed over an area nearly 500 miles east and west. Manifestly a traveler who spent the year 1885 in that region would have had much more difficulty in finding water and forage than one who traveled in the same places in 1905. During 1885 the rainfall was 42 per cent less than the average, and during 1905 it was 134 per cent more than the average. Let us suppose, for the sake of argument, that the average rainfall of southeastern Persia is 6 inches today and was 10 inches in the days of Alexander. If the rainfall from year to year varied as much in the past in Persia as it does now in New Mexico and Arizona, the rainfall during an ancient dry year, corresponding in character to 1885, would have been about 5.75 inches. On the other hand, if we suppose that the rainfall then averaged less than at present—let us say 4 inches—a wet year corresponding to 1905 in the American deserts might have had a rainfall of about 10 inches. This being the case, it is clear that our estimate of the importance of Alexander's march must depend largely on whether 325 B. C. was a wet year or a dry year. Inasmuch as we know nothing about this, we must fall back on the fact that a

large army accomplished a journey in a place where today even a small caravan usually finds great difficulty in procuring forage and water. Moreover, elephants were taken 180 miles across what is now an almost waterless desert, and yet the old historians make no comment on such a feat which today would be practically impossible. These things seem more in harmony with a change of climate than with uniformity. Nevertheless, it is not safe to place much reliance on them except when they are taken in conjunction with other evidence, such as the numerous ruins, which show that Makran was once far more densely populated than now seems possible. Taken by itself, such incidents as Alexander's march can not safely be used either as an argument for or against changes of climate.

The distinction between changes of temperature and changes of precipitation.—The third and last objection which we shall here consider is also the strongest. It is based on the condition of vegetation. The whole question is admirably set forth by Gregory,³² who gives not only his own results, but those of the ablest scholars who have preceded him. His conclusions are important because they represent one of the few cases where a definite statistical attempt is made to prove the exact condition of the climate of the past. After stating various less important reasons for believing that the climate of Palestine has not changed, he discusses vegetation. The following quotation indicates his line of thought. I have italicized a sentence near the beginning in order to call attention to the importance which Gregory and others lay on this particular kind of evidence:

"Some more certain test is necessary than the general conclusions which can be based upon the historical and geographical evidence of the Bible. In the absence of rain gauge and thermometric records, *the most precise test of climate is given by the vegetation; and fortunately the palm affords a very delicate test of the past climate of Palestine and the eastern Mediterranean.* . . . The date palm has three limits of growth which are determined by temperature; thus it does not reach full maturity or produce ripe fruit of good quality below the mean annual temperature of 69° F. The isothermal of 69° crosses southern Algeria near Biskra; it touches the northern coasts of Cyrenaica near Derna and passes Egypt near the mouth of the Nile, and then bends northward along the coast lands of Palestine.

"To the north of this line the date palm grows and produces fruit, which only ripens occasionally, and its quality deteriorates as the temperature falls below 69°. Between the isotherms of 68° and 64°, limits which include northern Algeria, most of Sicily, Malta, the southern parts of Greece and northern Syria, the dates produced are so unripe that they are not edible. In the next cooler zone, north of the isotherm of 62°, which enters Europe in southwestern

³² J. W. Gregory: Is the earth drying up? Geog. Jour., vol. 43, 1914, pp. 148-172 and 293-318.

Portugal, passes through Sardinia, enters Italy near Naples, crosses northern Greece and Asia Minor to the east of Smyrna, the date palm is grown only for its foliage, since it does not fruit.

"Hence at Benghazi, on the north African coast, the date palm is fertile, but produces fruit of poor quality. In Sicily and at Algiers the fruit ripens occasionally and at Rome and Nice the palm is grown only as an ornamental tree.

"The date palm therefore affords a test of variations in mean annual temperature of three grades between 62° and 69°.

"This test shows that the mean annual temperature of Palestine has not altered since Old Testament times. The palm tree now grows dates on the coast of Palestine and in the deep depression around the Dead Sea, but it does not produce fruit on the highlands of Judea. Its distribution in ancient times, as far as we can judge from the Bible, was exactly the same. It grew at 'Jericho, the city of palm trees' (Deut. xxxiv: 3 and 2; Chron. xxviii: 15), and at Engedi, on the western shore of the Dead Sea (2 Chron. xx: 2; Eccles. xxiv: 14); and though the palm does not still live at Jericho—the last apparently died in 1838—its disappearance must be due to neglect, for the only climatic change that would explain it would be an increase in cold or moisture. In olden times the date palm certainly grew on the highlands of Palestine; but apparently it never produced fruit there, for the Bible references to the palm are to its beauty and erect growth: 'The righteous shall flourish like the palm' (Ps. xcii: 12); 'They are upright as the palm tree' (Jer. x: 5); 'Thy stature is like to a palm tree' (Cant. vii: 7). It is used as a symbol of victory (Rev. vii: 9), but never praised as a source of food.

"Dates are not once referred to in the text of the Bible, but according to the marginal notes the word translated 'honey' in 2 Chron. xxxi: 5 may mean dates. . . .

"It appears, therefore, that the date palm had essentially the same distribution in Palestine in Old Testament times as it has now; and hence we may infer that the mean temperature was then the same as now. If the climate had been moister and cooler, the date could not have flourished at Jericho. If it had been warmer, the palms would have grown freely at higher levels and Jericho would not have held its distinction as *the* city of palm trees."³³

In the main Gregory's conclusions seem to be well grounded, although even according to his data a change of 2° or 3° in mean temperature would be perfectly feasible. It will be noticed, however, that they apply to temperature and not to rainfall. They merely prove that two thousand years ago the mean temperature of Palestine and the neighboring regions was not appreciably different from what it is today. This, however, is in no sense out of harmony with the hypothesis of this paper. As we have already seen, students of glaciation believe that during the last Glacial epoch the mean temperature of the earth as a whole was only 5° or 6° C. colder than at present. If the difference between the climate of today

³³ Geog. Jour., vol. 43, pp. 159-161.

and of the time of Christ is a tenth as great as the difference between the climate of today and that which prevailed at the culmination of the last Glacial epoch, the change in two thousand years has been of large dimensions. Yet this would require a rise of only half a degree centigrade in the mean temperature of Palestine. Manifestly, so slight a change would scarcely be detectable in the vegetation.

Examples of large variations in rainfall accompanied by slight variations in temperature.—The slowness of changes in mean temperature as compared with changes in rainfall may be judged from a comparison of wet and dry years in various regions. For example, at Berlin between 1866 and 1905 the ten most rainy years had an average precipitation of 670 mm. and a mean temperature of 9.15°C . On the other hand, the ten years of least rainfall had an average of 483 mm. and a mean temperature of 9.35° . In other words, a difference of 137 mm., or 39 per cent, in rainfall was accompanied by a difference of only 0.2°C . in temperature. Such contrasts between the variability of mean rainfall and mean temperature are observable not only when individual years are selected, but when much longer periods are taken. For instance, in the western Gulf region of the United States the two inland stations of Vicksburg, Mississippi, and Shreveport, Louisiana, and the two maritime stations of New Orleans, Louisiana, and Galveston, Texas, lie at the margins of an area about 400 miles long. During the ten years from 1875 to 1884 their rainfall averaged 59.4 inches,³⁴ while during the ten years from 1890 to 1899 it averaged only 42.4 inches. Even in a region so well watered as the Gulf States, such a change—40 per cent more in the first period than in the second—is important, and in drier regions it would have a great effect on habitability. Yet in spite of the magnitude of the change the mean temperature was not appreciably different, the average for the four stations being 67.36°F . during the more rainy decade and 66.94°F . during the less rainy decade—a difference of only 0.42°F . It is worth noticing that in this case the wetter period was also the warmer, whereas in Berlin it was the cooler. This is probably because a large part of the moisture of the Gulf States is brought by winds having a southerly component. Similar relationships are apparent in other places. We select Jerusalem because we are now discussing Palestine. At the time of writing, the data available in the Quarterly Journal of the Palestine Exploration Fund cover the years from 1882-1899 and 1903-1909. Among these 25 years the 13 which had most rain had an average of 34.1 inches and a temperature of 62.04°F . The 12 with least rain had 24.4

³⁴ See A. J. Henry: Secular variation of precipitation in the United States. Bull. Am. Geog. Soc., vol. 46, 1914, pp. 192-201.

inches and a temperature of 62.44° . A difference of 40 per cent in rainfall was accompanied by a difference of only 0.4° F. in temperature.

The facts set forth in the preceding paragraphs seem to show that extensive changes in precipitation and storminess can take place without appreciable changes of mean temperature. If such changed conditions can persist for ten years, as in one of our examples, there is no logical reason why they can not persist for a hundred or a thousand. The evidence of changes in climate during the historic period seems to suggest changes in precipitation much more than in temperature. Hence the strongest of all the arguments against historic changes of climate seems to be of relatively little weight, and the pulsatory hypothesis seems to be in accord with all the known facts.

DIVERSITY OF CHANGES OF CLIMATE IN DIFFERENT REGIONS

Before the true nature of climatic changes, whether historic or geologic, can be rightly understood another point needs emphasis. When the pulsatory hypothesis was first framed, it fell into the same error as the hypotheses of uniformity and of progressive change—that is, the assumption was made that the whole world is either growing drier or moister with each pulsation. A study of the ruins of Yucatan, in 1912, and of Guatemala, in 1913, as is explained in "The Climatic Factor," has led to the conclusion that the climate of those regions has changed in the opposite way from the changes which appear to have taken place in the desert regions farther north. These Maya ruins in Central America are in many cases located in regions of such heavy rainfall, such dense forests, and such malignant fevers that habitation is now practically impossible. The land can not be cultivated except in especially favorable places. The people are terribly weakened by disease and are among the lowest in Central America. Only a hundred miles from the unhealthy forests we find healthful areas, such as the coasts of Yucatan and the plateau of Guatemala. Here the vast majority of the population is gathered, the large towns are located, and the only progressive people are found. Nevertheless, in the past the region of the forests was the home of by far the most progressive people who are ever known to have lived in America previous to the days of Columbus. They alone brought to high perfection the art of sculpture; they were the only people who invented the art of writing. It seems scarcely credible that such a people would have lived in the worst possible habitat when far more favored regions were close at hand. Therefore it seems as if the climate of eastern Guatemala and Yucatan must have been relatively dry at some past time. The Maya chronology and traditions indicate that this was probably at the same time when moister

conditions apparently prevailed in the subarid or desert portions of the United States and Asia.

THE SHIFTING OF CLIMATIC ZONES—PENCK'S HYPOTHESIS

These considerations, and others described in the works already referred to, suggest that climatic changes consist largely of a shifting of the earth's climatic zones, sometimes poleward and sometimes equatorward. At times of equatorward shifting, polar conditions apparently cause glaciation in the northern portions of North America and Europe. In subtropical latitudes greater moisture prevails than formerly, for the storms of the temperate zone are shoved equatorward of their former courses. Still farther toward the equator the subtropical zone of aridity appears to invade the zone of equatorial rains, while the equatorial zone itself suffers contraction.

The hypothesis of the shifting of climatic zones, as outlined in the preceding paragraph, needs modification; but before proceeding to that it will be well to turn for a moment to the Glacial period and consider a recent article by Penck.³⁵ In this article, which appeared almost simultaneously with "The Climatic Factor," he explains the conditions of climate during the Glacial period by almost exactly the same hypothesis which I have offered in respect to historic changes of climate. Indeed, he apparently means that his hypothesis shall apply not only to glacial climates but to historic times, for near the beginning he speaks as follows:

"There are . . . many indications that, some centuries after the beginning of the Christian era, there was in central Asia a period of extreme dryness, which exercised a considerable influence on the conditions of settlement, and even, it would appear, upon migration." [This is the dry period which, in the curves of figures 13 and 14, culminates about 650 A. D.]

Penck sums up his conclusions as follows (page 288 ff.):

"Thus from the New as from the Old World we may draw the following conclusion: On the equatorial side of the Great Desert regions are flat pans occupied with slightly saline or occasionally fresh water, while on the polar side occur strongly saline lakes. . . . On the equatorial side . . . of the desert belts we have to do with rising lakes, on the polar side with shrinking pans. Both point to variations in climate, to increase of aridity on the polar side, to increase of humidity on the equatorial side. . . . Very characteristic are the phenomena in the Sahara. In the north there are living dunes consisting of bare wind-blown sand; the dead dunes, however, covered by sparse vegetation are confined to the south, and these dead dunes stretch beyond the arid region far into the humid zone along the right bank of the Niger. The dunes

³⁵ A. Penck: The shifting of the climatic belts. *Scottish Geographical Magazine*, vol. 30, 1914, pp. 281-291.

of the Kalahari are for the most part dead, and so stationary are they that the traveler can find his bearings from the number of dunes which he passes. The circumstances which have led here to the formation of dunes no longer obtain on the equatorial side of the desert zone, but prevail solely at the present day on the polar border.

"All this leads us to assume that the area of extreme aridity in Africa once lay much nearer the equator than it does today, exactly as was the case in both Americas, and guided by the phenomena of the Great Basin we may fix this period in the Ice Age. The great Ice Age presents itself, then, neither as a period of extreme cold—as was originally held—nor as a period of excessive humidity over the whole earth, but as a period during which the climate belts of the world lay some 4 or 5 degrees nearer the equator, while the snow-line was found more than 3,300 feet lower. . . . The shifting of the climate belts, however, during the Ice Age has never gone so far that one belt has entirely usurped the position of another."

In explanation of this supposed shifting of the climatic belts Penck states his belief in a lowering of temperature

"which would bring about not only an advance in the snow-line, but at the same time a shifting of all the climatic belts equatorwards. If the heat supply of the earth decreases, the atmospheric circulation will become less intense. The great areas of high pressure will become weaker and the horse-latitudes must move toward the equator. And it is they that determine the position of the arid areas upon the land-masses. Thus everything points to the fact that the . . . climate of the Ice Age was a period of reduced heat supply."

This last conclusion does not agree with those to which we seem to be led by a study of solar activity. Cold years, it will be remembered, are times not only of intense solar activity, but of intense movement of the air, as evidenced by an excess of tropical hurricanes and temperate cyclonic storms. This, however, need not be discussed further at this point. For our present purpose the importance of Penck's conclusion lies in two considerations. In the first place, it is somewhat remarkable that by lines of reasoning which are apparently wholly separate, students engaged in the study of glacial climates and of historic climates respectively should be led to almost identically the same hypothesis at approximately the same time.³⁶ In the second place, Penck has rendered an important service by calling the attention of geologists to the fact that during the Ice Age the same kind of climatic change did not take place everywhere, nor did all places suffer from a change of such a character as to produce any important results. Thus, to use Penck's terms, we have to do with rela-

³⁶ In this connection see C. E. P. Brooks: The meteorological conditions of an ice-sheet and their bearing on the desiccation of the globe. *Quart. Jour. Royal Meteorological Soc.*, vol. 40, 1914, pp. 53-70; and also W. F. Hume and J. I. Craig: The Glacial period and climatic change in northeastern Africa. *Rept. Brit. Asso.*, 1911, p. 382.

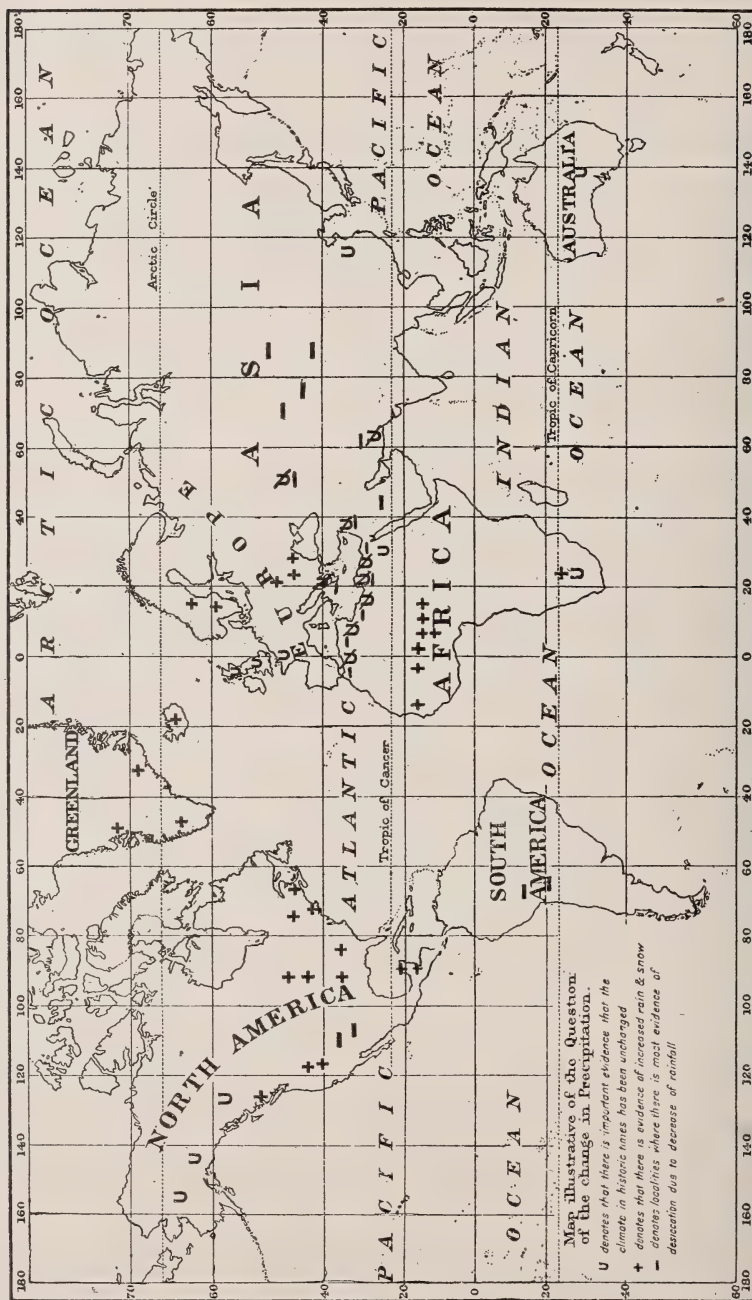


FIGURE 15.—Historic Changes in Precipitation. (After J. W. Gregory, with additions)

tively *constant* regions and relatively *shifting* regions. Gregory, in the article already cited, has gone even farther in this direction, and called the attention of geographers to the fact that an impartial survey of the evidence from the world as a whole shows that, so far as historic changes of climate are concerned, there are three types of areas: those which have grown drier, those which have grown moister, and those where no change has occurred. He has wisely adopted the plan of determining the type of change in each region separately and plotting it on a map of the world. This map is so valuable that it is here reproduced as figure 15. Two changes have been made in it. In the first place, I have added some plus signs in Yucatan and Guatemala to indicate increased precipitation on the basis of the ruins described above. In the second place, I have drawn lines through the U's, which indicate unchanged conditions in north Africa, Syria, Makran, and the Caspian region, and have added minus signs in their places. This is because the U's of the original map are largely based on the evidence of the palm and other vegetation, while almost no attention is paid to ruins, old strands, and other evidences which seem to me conclusive. Moreover, as Gregory himself states in a later publication,³⁷ he did not take the pulsatory hypothesis into consideration, and hence when he found evidence both of drier and wetter conditions he was forced to conclude that there had been no change. Other portions of the map remain as originally drawn; I do not feel that my knowledge is sufficient to justify any expression of opinion as to the portions south of the equator. In the northern hemisphere there may perhaps be some question as to China and the far northern portions of America, but the map at least represents the best knowledge that is available thus far.

Before proceeding to a consideration of the possible causes of changes of climate during historic times, let us sum up our conclusions as to their nature. The changes appear to be pulsatory in nature, but have no definite periodicity. The same phenomena recur in cycles of all magnitudes from the little cycles now in progress to those that have a length of thousands of years. In general the changes vary from region to region in such a way as to suggest that they are due to an alternate poleward and equatorward shifting of the great climatic belts. The matter is more complex than this, however, for in the same latitude one side of a continent may differ from the other. So far as can be detected, historic changes of climate do not seem to differ from those of the Glacial period or from the little variations that we see from year to year except in degree.

³⁷ *Geographical Journal*, vol. 44, 1914, p. 210.

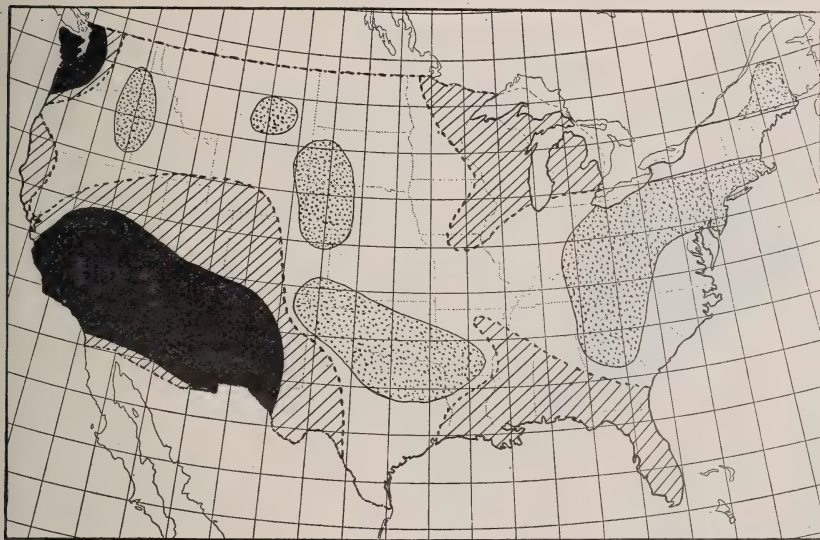
POSSIBLE EXPLANATIONS OF HISTORIC CHANGES OF CLIMATE

The meteorological hypothesis.—Let us now see how far each of the main hypotheses of climatic change is competent to explain these historic changes. Omitting the precessional hypothesis as no longer a possibility, we have six others before us. They are the meteorological, volcanic, deformational, and carbonic acid hypotheses, and the solar hypothesis in its old or "caloric" form and in its new or "cyclonic" form. The historic fluctuations, as shown in the California curve, for example, seem to be of such length and magnitude that they can scarcely be due to purely meteorological causes. The meteorological hypothesis is so vague, however, relying as it does on mere accidents, that it presents no tangible points of contact by which it can be proved or disproved. It stands, therefore, as a last resort so long as no other hypothesis offers a better explanation.

The volcanic hypothesis.—The next hypothesis is that of volcanic dust. We must assume, apparently, that just as the meteorological hypothesis is of great importance when we come to the details of the weather of every day, so the volcanic hypothesis is of importance at particular times. So far as the past 3,000 years are concerned, however, there seems to be no good reason for assuming that its importance has been any greater than during the last 30 years. The recorded volcanic eruptions show no apparent relation to the climatic changes indicated in the California curve. If there had been volcanic eruptions sufficient to cause the pronounced pulsation which figure 14 shows to have occurred between 1300 and 1500 A. D., it seems scarcely credible that they should have attracted so little attention. We can not assert this positively, however, for certain parts of the world where volcanoes are now important were not then known and their history is not recorded even by tradition. Our chief reason for believing that the volcanic hypothesis is of only minor importance is that this appears to be its position today, and that the same seems to be true of the geological past, as Professor Schuchert points out in "The Climatic Factor."

The solar hypothesis.—General discussion.—The hypotheses of crustal deformation and of carbonic acid gas were never intended as explanations of fluctuations which from the geological point of view are so small and short as those now before us. They are of the greatest importance when Glacial periods are considered, but for the present they do not concern us. The solar hypothesis, therefore, remains as the only one to be considered. Inasmuch as we have already seen reason to choose the cyclonic form in preference to the caloric, we shall confine our attention to the former. Two questions present themselves: In the first place,

How far do the changes which have taken place in historic times agree with those which now take place during the sun-spot cycle? In the second place, Is there any reason to think that the activity of sun-spots may have varied more in the past than at present? In answering these questions we shall confine ourselves to the United States and Europe, with only brief consideration of western Asia, since these are the only regions where sufficient data have as yet been worked up.



LEGEND



Over + 28 per cent.

0 to + 28 per cent.

0 to -14 per cent.

Less than -14 per cent.

The figures indicate the percentages by which the average storminess of the years of *maximum* sun-spots exceeds or falls short of the average storminess of the years of minimum sun-spots. The mean storminess for 30 years is taken as 100 per cent.

FIGURE 16.—Comparative Storminess of Nine Years of Maximum Sun-spots and Twelve Years of Minimum Sun-spots in the United States in Percentages of mean Storminess for Thirty Years.

This diagram is the same as figure 7, except that it has been calculated in percentages, and covers only the United States

The United States.—The United States is probably the best of all areas for the study of the problem now before us, for nowhere else is so large a body of reliable and homogeneous observations easily available. On the basis of the observations of the United States Weather Bureau, the maps of figures 16 and 17 have been compiled. Figure 16 shows the

extent to which the number of storms during years of many sun-spots exceeds or falls short of the number during years of few spots. It embodies the same material as figure 7. The only difference is that the percentage of excess or deficiency has been used instead of the actual number of storm centers, and lines have been drawn so as to divide the entire area into four parts of approximately the same area. The interpretation is simple. The heavy black shading means that when sun-spots are



LEGEND



Over + 16 per cent.
0 to + 16 per cent.
0 to - 8 per cent.
Less than - 8 per cent.

The figures indicate the percentages by which the average rainfall of the years of *maximum* sun-spots exceeds or falls short of the average of the years of minimum spots. The mean precipitation since records have been kept is taken as 100 per cent.

FIGURE 17.—Comparative Precipitation of Nine Years of Maximum Sun-spots and Nine Years of Minimum Sun-spots in Percentages of the mean Precipitation

numerous storms are abundant; the dotted areas indicate that when spots are numerous storms are comparatively few. The other two kinds of areas—that is, those shaded by means of lines and those left unshaded—indicate that the amount of storminess does not change greatly, although where the lines occur there is a slight increase in storms at sun-spot maxima and in the other areas a slight decrease.

Figure 17 is constructed according to the same method as figure 16 except that rainfall instead of storminess is used. It is based on all the

stations in the United States where rainfall records go back as far as 1877. In some cases the records are imperfect and have been supplemented by those from neighboring stations. Elsewhere two or three stations which lie close together have been combined. The entire number of stations is 183. The 33 years from 1877 to 1909 contain three sun-spot cycles. The three years of minimum and of maximum spots in each of the three cycles are the same that have been used in Kullmer's work on storm tracks. They are as follows:

Years of minimum spots.	Sun-spot numbers.	Years of maximum spots.	Sun-spot numbers.
1877	12.3	1882	59.7
1878	3.4	1883	63.7
1879	6.0	1884	63.5
1888	6.8	1893	73.0
1889	6.3	1894	84.9
1890	7.1	1895	78.0
1900	9.5	1905	58.6
1901	2.7	1906	52.8
1902	4.7	1907	64.5

Average for nine years of minimum sun-spots, 6.5.

Average for nine years of maximum sun-spots, 65.5.

For each station the average rainfall for the nine years of minimum and for the nine years of maximum has been computed, and the departure of this from the mean for the entire period covered by records has been obtained. Then the difference between the departure when sun-spots were few and when sun-spots were many has been ascertained. This has been reduced to percentages of the mean rainfall and has been inserted on the map. This is better than the use of the actual differences, since a change of 2 inches in a place where the average rainfall is 10 inches is much more important than a change of 2 inches where the rainfall is 50 inches. By the use of percentages these figures would appear as 20 per cent in one case and 4 per cent in the other. The shading of figure 17 has the same significance as in figure 16. The two maps show certain differences, partly because the map of storms is based on a slightly larger number of years than the other; but much more because the rainfall map includes not only the precipitation which accompanies ordinary cyclonic storms, but that which comes in thunder-storms and other local showers.

In spite of minor differences the two maps show the same main features. They indicate the general conditions which would be expected if the conditions which now prevail at times of many sun-spots were to become permanent. The most prominent feature is a large black area in

the southwest where the rainfall is decidedly more at times of many sun-spots than of few. This is the area from which most of the American evidence of desiccation during the past few thousand years is derived. It includes the Big Trees of California and the ruins of New Mexico and Arizona. Although many authors, here as elsewhere, have doubted whether the evidence of climatic changes is convincing, there seems to be a growing tendency to think that such is the case. The matter has been well set forth by Hewett, Henderson, and Robbins,³⁸ who come to the conclusion that the climate has suffered a distinct change toward aridity since the days when the main Pueblo ruins were in their prime. On Gregory's map, figure 15, this region is shown as one of the chief areas where a change of this kind has occurred.

The next feature of figures 16 and 17 is a discontinuous belt of scanty rainfall at times of many sun-spots. It begins in Montana or Idaho, runs southeastward, and then southward along the great plains to the Gulf of Mexico. The center of this belt lies in the middle of the United States, not far from the center of Kansas. Here the deficiency during years of many sun-spots amounts to 30 per cent of the average rainfall. It is apparently a phenomenon which recurs whenever sun-spots are numerous, for each of the three sun-spot cycles shows it. The figures for Hays, Kansas, the station where the deficiency is most marked, are as follows:

Date of minimum sun-spots.	Rainfall during 3 years of minimum sun-spots.	Date of maximum sun-spots.	Rainfall during 3 years of maximum sun-spots.	Amount by which rainfall of maximum is less than that of minimum.
	<i>Inches.</i>		<i>Inches.</i>	<i>Inches.</i>
1877-1879...	23.7	1882-1884..	18.8	9.9
1888-1890...	20.9	1892-1895..	14.2	6.7
1900-1902...	28.0	1905-1907.	24.1	3.9

The third prominent feature of the maps is an area of deficiency in the northern part of the Atlantic Coast region. The rest of the country shows no distinct tendency toward either excess or deficiency. In general one may say that, except for the Southwest, the United States is a region where areas of diminished precipitation during times of many sun-spots are scattered in such a way that they are the most prominent feature. This, again, is in agreement with Gregory's map, where all of the United States except the Southwest is spotted with plus signs, indicating an increase of rainfall. It is also in agreement with Arctowski's^{38a}

³⁸ The Physiography of the Rio Grande Valley in New Mexico in Relation to Pueblo Culture. Washington, 1913.

^{38a} H. Arctowski: Changes in the distribution of temperature in Europe and North America. *Annals N. Y. Academy of Sci.*, vol. 24, 1914, p. 103.

conclusions as to variations of temperature. He finds that in New Mexico, Arizona, and southern California variations of temperature "display a striking preference to belong to the inverse type, and that in Pennsylvania and Oregon the direct type must predominate." By direct he means that the temperature rises and falls in harmony with that of Arequipa, whose cycle of two or more years is taken as the standard of the pleions and antipleions of temperature which seem to arise from variations in solar radiation.

Asia.—In the Old World it has not been possible to work out the matter so carefully as in the New, partly because the problem is more complex and partly because there is no uniform series of records easily available. In Asia most authorities, as is indicated by Gregory's map, believe that the climate of the center of the continent has changed. These changes appear to have been of essentially the same sort as those of the southwestern United States, as is indicated by the trees of California, the fluctuations of the Caspian Sea, and other evidences which form the basis of the curves of figure 13. Here, then, just as in the United States, the distribution of past climatic changes agrees with what we should expect if the changes were due to variations in the sun. In western Asia and the Mediterranean region I am strongly inclined to the same opinion for reasons already stated. Another reason for holding this view is that in its relation to the continent and in its general climatic conditions this area closely resembles the portion of the United States where the rainfall seems to have diminished.

Europe.—In Europe it will within a few years be possible to make maps like the two of the United States shown in figures 16 and 17. Meanwhile we must turn to other lines of evidence. In that continent, as we have seen, periods of sun-spots appear to be characterized by continental conditions with dry winters and wet summers. At such times the barometric gradients are steepened, so that storms in the peripheral regions tend to be more violent than at times of sun-spot minima. The only evidence which we have as to changes of climate in Europe suggests that such conditions prevailed at certain times many centuries ago. Tycho Brahe, during the years 1582-1597, made meteorological observations on a little island in the North Sea. He recorded the direction of the wind and the occurrence of days characterized by cloudiness, rainfall, sun, and hail. His data have been compared with those of modern times, and the results are summed up in Hann's *Klimatologie*, volume 1, pages 346-347. The general conclusion is that there is some indication that in Tycho Brahe's day the climate of western Europe was a trifle more continental than now, but, as Hann points out, the difference between then and now was

very slight. It amounts to no more than we could find at present by selecting two periods of 14 years each. This is interesting because the end of the sixteenth century, according to our California curve, was a time when the climate was practically the same as at present, although the California curve may indicate a slightly greater precipitation than now. This means that the observations of Tycho Brahe agree with what we should expect. Going farther back, we find that the fourteenth century was highly peculiar. This has been discussed in various places, but is summed up by Pettersson.³⁹ According to him, the fourteenth century shows

“a record of extreme climatic variations. In the cold winters the rivers Rhine, Danube, Thames, and Po were frozen for weeks and months. On these cold winters there followed violent floods, so that the rivers mentioned inundated their valleys. Such floods are recorded in 55 summers in the 14th century. There is, of course, nothing astonishing in the fact that the inundations of the great rivers of Europe were more devastating 600 to 700 years ago than in our days, when the flow of the rivers has been regulated by canals, locks, etc.; but still the inundations in the 13th and 14th centuries must have surpassed everything of that kind which has occurred since then. In 1342 the waters of the Rhine rose so high that they inundated the city of Mayence and the Cathedral ‘usque ad cingulum hominis.’ The walls of Cologne were flooded so that they could be passed by boats in July. This occurred also in 1374 in the midst of the month of February, which is of course an unusual season for disasters of the kind. Again in other years the drought was so intense that the same rivers, the Danube, Rhine, and others, nearly dried up, and the Rhine could be forded at Cologne. This happened at least twice in the same century. There is one exceptional summer of such evil record that centuries afterwards it was spoken of as ‘the old hot summer of 1357.’”

Pettersson goes on to speak of two oceanic phenomena on which the old chronicles lay greater stress than on all others:

“The first [is] the great storm-floods on the coasts of the North Sea and the Baltic, which occurred so frequently that not less than nineteen floods of a destructiveness unparalleled in later times are recorded from the 14th century. The coastline of the North Sea was completely altered by these floods. Thus on January 16, 1300, half of the island Heligoland and many other islands were engulfed by the sea. The same fate overtook the island of Borkum: torn into several islands by the storm-flood of January 16, which remoulded the Frisian Islands into their present shape, when also Wendingstadt, on the island of Sylt, and Thiryu parishes were engulfed. This flood is known under the name of ‘the great man-drowning.’ The coasts of the Baltic also were exposed to storm-floods of unparalleled violence. On November 1, 1304, the island of Ruden was torn asunder from Rugen by the force of the waves. Time does not allow me to dwell upon individual disasters of this kind, but it will be well to

³⁹ O. Pettersson: The connection between hydrographical and meteorological phenomena. Quarterly Journal of the Royal Meteorological Society, vol. 38, pp. 174-175.

note that of the nineteen great floods on record eighteen occurred in the cold season between the autumnal and vernal equinoxes.

"The second remarkable phenomenon mentioned by the chronicles is the freezing of the entire Baltic, which occurred many times during the cold winters of these centuries. On such occasions it was possible to travel with carriages over the ice from Sweden to Bornholm and from Denmark to the German coast (Lubeck), and in some cases even from Gotland to the coast of Estland."

These quotations are particularly significant when compared with the conclusions drawn from the growth of trees in Germany and the distribution of storms as given by Kullmer. A careful reading of Pettersson's statements shows that we have to deal with two distinct types of phenomena. In the first place, the climate of central Europe seems to have been peculiarly continental during the fourteenth century. The winters were so cold that the rivers froze, and the summers were so wet that there were floods every other year or oftener. This seems to be merely an intensification of the conditions which we have already seen to prevail at the present time during periods of many sun-spots, as indicated by the growth of the Eberswalde trees and by the number of storms in winter as compared with summer. The prevalence of droughts, especially in the spring, is also not inconsistent with the existence of floods at other seasons, for one of the chief characteristics of a continental climate is that the variations from one season to another are more marked than in oceanic climates. Even the summer droughts are typically continental, for when continental conditions prevail, the difference between the same season in different years is extreme, as is well illustrated in Kansas.

The second type of phenomena described by Pettersson is, as he takes pains to state, peculiarly oceanic in character. It consists of two parts, both of which are precisely what would be expected if a highly continental climate prevailed over the land. In the first place, at certain times the cold area of high pressure, which is the predominating characteristic of a continent during the winter, apparently spread out over the neighboring oceans. Under such conditions an inland sea, such as the Baltic, would be frozen, so that carriages could cross the ice even in the far west. In the second place, because of the unusually high pressure over the continent, the barometric gradients apparently became intensified. Hence at the margin of the continental high-pressure area the winds were unusually strong and the storms of corresponding severity. Some of these storms may have passed entirely along oceanic tracks, while others invaded the borders of the land, and gave rise to the floods and to the wearing away of the coast described by Pettersson.

Another highly significant fact in this connection appears in the curve

of the trees of California as given in figure 14. There it will be seen that the fourteenth century was a period of peculiarly rapid growth. It was the last great epoch when the growth of the trees approximated that of earlier centuries, such as the periods centering about 1000 A. D. and at the time of Christ. The high position of the curve in the middle of the fourteenth century is the condition which we should naturally expect at a time of many sun-spots. In this respect it agrees exactly with the conditions in Europe.

THE PROBABILITY OF GREAT CHANGES IN SUN-SPOTS IN THE PAST

PETTERSSON'S SUN-SPOT HYPOTHESIS

The importance of the data collected by Pettersson is not yet exhausted. He definitely connects sun-spots with the climatic vicissitudes which he describes:

"In Europe the sun-spots were discovered as recently as in 1610, but in China they were observed 1,500 years earlier, and are recorded in Chinese annals from the first century. In these Chinese records, of course, only such years as were marked by a great number of spots are registered; and it is remarkable that those years occur in groups with long intervals, and that certain centuries are noted by an unusual frequency of spots. Thus in the fourteenth century the years from 1370 to 1385 are noted for sun-spot maxima. So long a period of maxima had not occurred since the end of the fourth century, and Wolf therefore considers that an absolute maximum of spots occurred about 1372."

The importance of Pettersson's connection of sun-spots with changes of climate scarcely needs to be pointed out. It is completely in accord with what we should expect. The agreement with expectation pertains even to details. For example, the curve of the storm frequency in the main area of northward shifting in North America (figure 9) led us to suspect that the apparently connected phenomena of the sun and the earth reach their maxima at slightly different times. We concluded, it will be remembered, that the conditions look as if a certain force sets the atmospheres of both the earth and the sun in motion at the same time, but that the earth's atmosphere reaches its maximum activity sooner than that of the sun and falls into quiescence sooner. The fact that the California curve reaches its maximum a few decades earlier than the date assigned by Wolf for the absolute maximum of sun-spots harmonizes with this idea. I do not lay much stress on this, however, partly because we are as yet so totally in the dark as to the real cause of both sun-spots and storms and partly because of the considerations advanced in the next paragraph.

THE SCARCITY OF EARLY SUN-SPOT DATA

As is already clear to the reader, I am strongly inclined to believe that Pettersson has discovered a genuine connection between sun-spots and the peculiar climatic conditions of Europe in the fourteenth century. Nevertheless it is important that we should clearly recognize the difficulties in the way of any exact knowledge as to the sun-spots of past times. At a period as remote as the fourteenth century the difficulty is great. When still earlier periods are considered, the difficulty increases in geometrical ratio; so that we can scarcely hope ever to have any exact knowledge based on actual observation. Previous to the invention of the telescope it was almost impossible to form any accurate idea of the activity of the sun's surface. Occasionally spots of unusual size might be visible to the naked eye. This, however, in itself is not a proof that the sun possessed an unusual degree of spottedness. Often a large spot occurs at a time when the general surface shows a minimum amount of disturbance. Another reason for laying little weight on the sun-spot records previous to 1600 is that there was no one whose duty it was to record the occurrence of spots. The fact that a certain observer who was interested in the matter recorded a large number may lead us to think that his particular period was marked by intense solar activity. This may merely mean, however, that at other periods of much greater activity there happened to be no one who was interested enough to record the matter.⁴⁰

MAJOR SUN-SPOT CYCLES OF THE PRESENT TIME

In view of the difficulty of obtaining exact knowledge of sun-spots more than two or three hundred years ago, let us examine the matter in another way. Let us look at the sun-spot curve since 1749, the date when accurate figures first become available, and let us see what it suggests as to the laws of variability. The curve is given in figure 18, where the sun-spot numbers for each year are plotted according to Wolfer's tables. Dotted lines have been added connecting the various maxima and also the minima. So much is said about the 11-year period of the solar spots that we are apt to think that this is their most important variation. Next after this in importance in our ordinary thought of the matter is the 35-year cycle of Brückner. A glance at the curve before us, however, shows that a still larger cycle is quite as important. Beginning with 1750, we see that during the first year of maxima the sun-spot number was about 83.4.

⁴⁰ Our knowledge of the whole matter is largely due to Wolf. His observations, together with later information as to both sun-spots and the related phenomena of polar lights, are summed up by H. Fritz in the *Zurich Vierteljahrschrift*, vol. 38, 1893, pp. 77-107. An abstract of this article is given in *Annalen der Physik und Chemie*, Beiblatter, v. 17, 1893, p. 930.

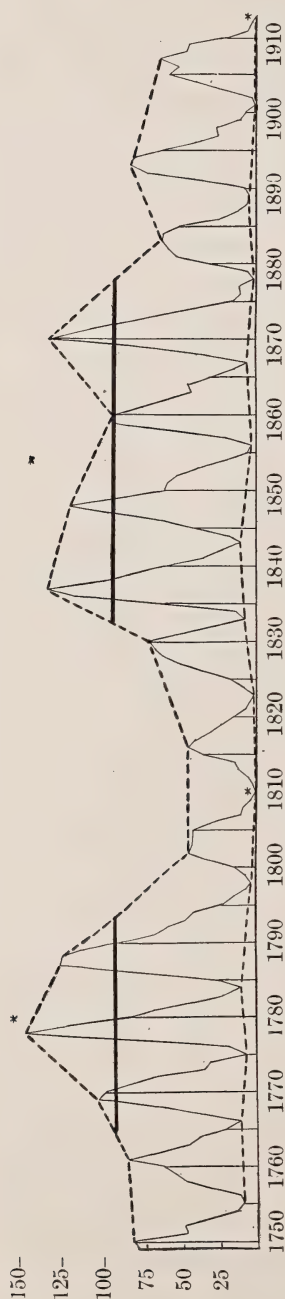


FIGURE 18.—Major and Minor Sun-spot Cycles

The asterisks indicate two absolute minima of sun-spots in 1810 and 1913, and the middle years (1780 and 1854) of two periods when the sun-spot maxima never fell below 95

Then in succeeding cycles the maxima become more and more pronounced until, in 1778, the number was 154.4, or nearly twice as much as in 1750. Thereafter there is a decline to only 45.8 in 1816. An increase again follows, and from 1837 to 1870 we have four maxima, all of which are above 95. Then the number of spots falls off once more. If we look at the dotted line joining the minima we see that it rises and falls in the same way as the line joining the maxima, although not nearly as much. In 1810 there were no sun-spots. An equally inactive state of the sun was not again attained until 1913. The low state of both the maxima and minima at these two dates indicates a cycle whose length is somewhere near a century. The interval from one main maximum to the next happens in this case to be somewhat different from the interval between the chief minima. The first great maximum comes in 1778. Then comes another period of maxima with two main crests, one in 1837 and one in 1870. In figure 18 two heavy lines have been drawn at a height of 95 in order to bring out the periods of many sun-spots as compared with the periods of few. It is remarkable that not only does the height of the maxima vary at different periods, but the length of the individual cycles varies in the same way. Apparently at the end of a period of abundant solar activity the active force, whatever it may have been, becomes dormant and we have a long interval before another and much smaller maximum appears. For instance, the interval from

the maximum of 1787 to that of 1804 is 17 years and from 1870 to 1883 is 13 years, the average of the two being 15 years. While the solar activity remains low, the length of the intervals from maximum to maximum remains long. For instance, the five cycles between maxima which have sun-spot numbers of less than 95 have an average length of 12.2 years. The remaining cycles—that is, the seven which precede sun-spot maxima of 95 or higher—have an average length of 9.4 years. From this we see that in a period of about 100 years the sun-spots pass through a great cycle which begins with a very long minor cycle and a low maximum. After this the length of the minor cycle decreases and the maxima rise higher and higher. Manifestly, as our diagram shows, the great or major cycle is quite as real as the so-called 11-year or minor cycle, which really varies from 7 to 17 years. The more we study sun-spots the more we see that they are characterized by great irregularity. All attempts to find a definite period have broken down. There may be a distinct periodicity for a few cycles, but it soon changes. If sun-spots can vary in a minor cycle having a length from 7 to 17 years, in a larger cycle which perhaps has a length of about 50 years, as made out by Fritz, and in a still larger one, which has a length of perhaps a century, it would seem probable that they can also vary in cycles of very much greater length and greater intensity.

THE NATURE OF SUN-SPOTS

At this point a word may well be added as to the nature of sun-spots. Recent studies seem to indicate that they are probably cyclonic vortices which partake somewhat of the nature of volcanoes and somewhat of the nature of cyclonic storms. Of course, in a highly heated body like the sun, where everything, on the surface at least, is in a gaseous condition, we can not expect any exact analogy with our solid earth. Nevertheless the resemblances are striking. Like both volcanoes and cyclones, the sun-spots appear to carry material from lower to higher levels. It is thought by Hale and others that the material which is carried out is cooled somewhat, and that this cooling may cause it to act like a cloud and thus appear dark. Humphreys has suggested that perhaps a certain amount of solar radiation is actually cut off in this way. Another respect in which sun-spots resemble cyclones is that they seem to have a spiral motion resembling that of the inblowing winds of our terrestrial storms. They do not travel rapidly like cyclones, but they are not stationary like volcanoes. Another important characteristic is that they are highly electric in their constitution, and in this quality they resemble most volcanic discharges and many cyclonic storms. Still another characteristic is that they seem

to be somehow allied to solar prominences, which in a rough way may be likened to clouds in the terrestrial atmosphere. Perhaps the prominences are more analogous to the clouds of dust sent out by volcanoes than to anything else, but we do not yet know enough of their character to speak at all positively.

Like the volcanoes and cyclonic storms of the earth, sun-spots appear to be phenomena pertaining merely to the outer layer of the body on which they occur. Their activity varies in much the same irregular way as that of our storms. Roughly they are periodic, but the intervals may be longer or shorter. Volcanoes, too, vary in the same irregular way, for sometimes we have periods of great numbers of eruptions and at others the earth becomes quiescent. Both cyclones and volcanoes can vary greatly on the earth's surface without necessitating any marked variations in the mean temperature of that body and in the amount of heat which it radiates to space. Even the eruption of several hundred square miles of lava would not for any great length of time cause a measurable difference in the amount of heat which would be sent out from the earth to the sun. Such a volcano might erupt again and again at intervals for a century, but even then it would play a small and hardly noticeable part in the gradual cooling of the earth. In the same way there seems reason to think that although the mean temperature of the sun as a whole may remain unchanged, the activity of its surface as shown in the spots may vary as greatly as has the activity of volcanoes on the earth's surface.

THE CONNECTION BETWEEN HISTORIC CHANGES OF CLIMATE AND THE GLACIAL PERIOD

COMPLEXITY OF POST-GLACIAL CLIMATIC VARIATIONS IN THE SOUTHWEST

Before turning to the Glacial period let us examine the evidence afforded by the extinct or diminished lakes of the arid regions of the United States. The old strands of such lakes are almost universally regarded as furnishing one of the most reliable records of ancient climatic variations. The number, relative altitude, and relative degree of prominence of such strands, however, may differ greatly in two adjacent basins, even though both have been subjected to the same climatic changes. An example will make the matter clear. Suppose that two basins possess precisely the same climate and are each occupied by a lake 10 miles in diameter. Let there be no difference between the two except that in one basin the lake floor is exceedingly flat, so that the slope from the shores of the lake toward the center is only 1 foot in 500. In the other basin the floor slopes more decidedly—let us say 1 foot in 25. Let us further

suppose that the two basins are so similar that a decrease of 5 or 10 per cent in the rainfall causes the same diminution in the amount of water reaching each lake. Under such circumstances each will eventually contract to the same degree, for the size of a lake in an arid region is determined by the point at which the supply of water is balanced by the evaporation. If the supply and the evaporation are equal, the lakes must have the same area without respect to their depth or to the surrounding topography. This statement is so axiomatic that it would not be necessary were it not that it is often overlooked.*

Supposing, then, that both lakes contract so that their shores retire an average distance of 500 feet, what sort of new strands will be formed? The first lake will fall only one foot. It will be bordered by shores so flat that the waves will have little opportunity to cut bluffs or form beaches. What little work they accomplish will be so nearly at the same level as that of the original strand that in later times, if the lake disappears, it will be impossible to distinguish the one from the other. In the other lake, on the contrary, the fact that the bottom of the lake slopes at

* This statement must not be understood as meaning that two lakes having the same water supply and climate, but differing in topography, are always of the same size. When climatic conditions remain stable for a considerable time such lakes must become of essentially the same size, but during the process of change they may act differently. The matter may be illustrated by supposing that under certain climatic conditions we have two similar lakes (A and B), nearly square in form, and having an area of 100 square miles. Suppose that climatically both are subject to precisely the same conditions, and that their only point of difference is that A is extremely shallow and its bottom slopes only 1 foot in 600, while B is of a more common type, with a slope of 1 in 24. Suppose that the climate has been stable so long that the water supply and the evaporation are exactly equal. Then let the climate suddenly change so that the water supply of each lake is reduced 10 per cent. Let the new rate of evaporation be 40 inches per year in each. Supposing the climate to remain uniform under the new conditions, the course of events would be as shown in the following table:

	Annual reduction in level due to excess of evaporation over precipitation (inches).		Area after level has been reduced (square miles).		Total reduction of level (inches).	
	A.	B.	A.	B.	A.	B.
First year.....	4.00	4.00	98.41	99.92	4.00	4.00
Second year.....	3.42	3.98	97.02	99.87	7.42	7.98
Third year.....	2.89	3.95	96.04	99.81	10.31	11.93
Fourth year.....	2.50	3.93	95.26	99.75	12.81	15.86
Fifth year.....	2.21	3.91	94.47	99.68	15.02	19.77

If this table were continued, we should see that the shallow lake (A) would in a few years be reduced to an area of approximately 90 square miles, the limit toward which it would tend under the assumed conditions. It would fall about 2 feet (26 inches). The other, although its rate of fall is much the faster of the two, would be far slower in reaching a condition near the point of equilibrium, for a vast amount of water would have to be evaporated before the level could be reduced to such a point that the evaporation would be no greater than the supply. Absolute equilibrium from the mathematical point of view would only be attained after an infinite series of years; but for the practical purposes of geology, with which alone we are concerned, essential equilibrium would be reached in a few centuries at a level 50 to 55 feet below the original surface. These are the conditions referred to in the text.

the rate of 1 foot in 25 will oblige the water to fall 20 feet before the evaporation surface becomes small enough to be in equilibrium with the diminished supply of water. If the lake remains at this level for a few decades, distinct beaches and bluffs will be formed, for the lake will not be so shallow as to prevent the waves from breaking on the shore, and the slope of the land will permit wave erosion to proceed rapidly. When this lake disappears, its two positions will be marked by strands whose elevation will differ by 20 feet. These will form a pronounced and easily deciphered record of a climatic fluctuation which affected both lakes equally, but whose existence would be quite unknown if only the first of our two basins were studied.

The importance of these considerations lies in the fact that the basins of our Western States show an extraordinary variation in the number of their old lake terraces. This variation may mean in part that the climatic changes of the past, like the little changes of the present, as shown in our maps of rainfall and storms, differed in intensity from place to place. In the quotation which will follow shortly the reader will notice that the greatest number of old strands is found not far from the center of the area shaded black in figures 16 and 17. This is what would be expected, for from the center outward the degree of change diminishes until the zero line is reached, after which it becomes of an opposite type. The variation in the number of terraces also means that topographic conditions sometimes favor the preservation of records of slight changes, and sometimes do not permit even the larger changes to leave a permanent record. Hence, if we desire to know the true degree of changeability, we must focus attention on the places where the fullest records have been preserved.

FREE'S DATA AS TO OLD STRANDS IN THE SOUTHWEST

Although the history of the main events in the histories of lakes Bonneville and Lahontan is familiar, there are many other old lakes whose very existence is almost unknown. They are now being studied, however, and are giving most interesting results. Probably the most comprehensive study yet made is that of Mr. E. E. Free, who, in his investigation of potash and other salines on behalf of the United States Department of Agriculture, has spent several years in traveling about among the desert basins. He has published a summary of the topographic features of those parts of North America which are without drainage to the sea, and has distinguished 126 basins which are of sufficient importance to deserve individual consideration. In addition to this he has most courteously permitted me to use some of his unpublished

data and has prepared a summary which is inserted below. It is a pleasure to express my appreciation of Mr. Free's work and my gratitude for his cooperation.¹

"Sixty-two basins either contain unmistakable lake evidences or belong to one of the three great lake groups mentioned below. Two of these, the Lake Lahontan and Lake Bonneville groups, comprise twenty-nine present basins,² some of which were once flooded by the waters of the lakes, while some were higher tributary valleys now cut off hydrographically by the decay of the drainage systems. At its maximum stage Lake Bonneville discharged into the Columbia River. Lake Lahontan never overflowed. Each, however, has left a complex series of strands, terraces, and wave-bars, recording the fluctuations of its rise and fall. Wherever the waters of Bonneville or Lahontan invaded the smaller subsidiary basins the walls of the latter carry the terrace systems of the greater lakes, but as the fall of the waters exposed the divides and split the larger basins into smaller the subsidiary basins developed lower terrace systems different in each. This, complicated by temporary overflow from one subsidiary basin into another, has produced a total record of much complexity and which has not yet been read in full detail.³

"The third group, that of the Owens-Searle lake chain, has been studied only recently, especially by H. S. Gale and by the writer. It appears that Owens Lake formerly stood at a higher level and overflowed southward through the pass now followed by the Owens Valley branch of the Southern Pacific Railway. This discharge filled and overflowed the shallow basin of China Lake,

¹ See United States Department of Agriculture, Bulletin 54, 1914, by E. E. Free. This contains full topographic details. A list of undrained basins is given on pages 60-61, and all of these are shown on an accompanying map. For the convenience of readers who may wish to refer to this list, Mr. Free divides the basins into the following groups in addition to the main group treated in the present paper:

(1) Twenty-two basins not sufficiently known to the writer to enable discussion concerning the existence or non-existence of lake relicts. These basins are: Guano, Oregon; Long Valley, Huntoon, Goldfield, Penoyer, Gold Flat, Emigrant, Frenchman Flat, Sheep Range, Spring Valley, and Opal Mountain, Nevada; Saline Valley, Eureka, Willard, Granite Mountain, Owl, Ivanpah, and Danby Lake, California; Salt Basin, Texas; Laguna Guzman, Mexico; Red Desert, Wyoming, and Hualpai, Arizona.

(2) Thirty-two additional basins were formerly hydrographic parts of other basins or were drained to the sea. These are: Silver Lake, Summer Lake, Harney, White Horse, and Goose Lake, Oregon; Thousand Creek, Fairview, Acme, Luning, Mina, Kingston, Smiths Creek, Kawich, Yucca, Indian Spring, Pintwater, Lee Canyon, and Gannett, Nevada; Klamath Lakes, Aurora, Mesquite Lake, Dale Lake, Palen Lake, Bristol Lake, Cadiz Lake, Laguna Maquata, and Carriso Plains, California; Pinos Wells, Lordsburg Dry Lake, and the Plains of San Augustine, New Mexico; Cochise, Arizona, and San Luis Valley, Colorado.

(3) Of the remaining basins there are ten in which careful examination has failed to disclose unmistakable evidences of former lakes. These are: Christmas Lake, Oregon; Gabbs Valley, Rhodes, Garfield, Teels, Monte Cristo, Clayton, and Edwards Creek, Nevada, and Deep Springs Valley and Kane, California. In two of these cases (Christmas Lake and Kane) there is a doubtful possibility of previous overflow, and in four others (Garfield, Teels, Edwards Creek, and Deep Springs Valley) the writer has found topographic forms which may possibly be lake terraces, but which are too doubtful to justify a definite conclusion to that effect.

² These are individually indicated in the list of Bulletin 54, above referred to.

³ Active work is in progress on this problem mainly by Prof. J. Claude Jones, of the University of Nevada, and by Mr. H. S. Gale, of the U. S. Geological Survey.

which spilled in turn into the deep structural basin now occupied by the Searles "lake" or salt marsh. The Searles Basin filled to a depth of 600 feet above its present bottom and overflowed into the Panamint Valley to the east. It is believed by Gale⁴ that the Panamint also was filled to the point of overflow and discharged, for a time at least, into Death Valley over a pass about 1,000 feet above the floor of the tributary valley. There existed, therefore, a chain of four lakes—Owens, China, Searles, and Panamint—each of which overflowed, the final overflow being into Death Valley, in which no evidences of lake conditions have been found. In the basins of all four of these lakes terrace systems record the earlier conditions. In Owens the highest and best developed terrace is about 250 feet above the present lake level and marks the level of discharge. Below this are fairly well marked strands at approximately 20, 30, and 50 feet above the present lake, and probably one higher terrace, now much eroded, at perhaps about 150 feet. The basin of China Lake contains similar strands below the level of overflow, but the writer does not know them in detail. In the basin of the Searles salt marsh the overflow terrace is very well developed at approximately 600 feet above the present bottom. Below this is a series of many strands, of which the writer has counted 21, at approximately the following elevations in feet above the present bottom of the basin: 550, 530, 500, 490, 475, 430, 385, 350, 310, 265, 240, 220, 195, 105, 90, 75, 65, 45, 40, 35, and 20. The 500-foot strand is particularly well developed, being almost as deeply cut as is the overflow (600-foot) terrace. In the lower 200 feet of this terrace series very faint strands 18 inches to 2 feet apart can sometimes be traced between the terraces noted. It seems probable that these fainter markings represent annual stages in the retreat of the ancient lake. A terrace system exists in the Panamint Basin, but is not known to the writer in detail.

"In addition to the probable overflow from the Owens-Searles lake chain, Death Valley formerly received water from the drainage systems of the Amargosa and Mohave rivers, the former of which still flows in part to the sink. Several small basins now undrained were once tributary to one or the other of these rivers and contributed their quota to the former flow.⁵ This means that Death Valley must have received a considerable drainage quite regardless of the volume of the overflow from the Panamint. Nevertheless, very careful search has failed to disclose any vestige of former lake conditions in Death Valley, this surprising circumstance remaining quite unexplained.

"There remain eighteen individual undrained basins unconnected with any of the three larger groups and which contain unmistakable evidences of the former presence of lakes. In each case these lakes were individual and hydrographically unrelated to one another. In only one case (the Salton) is there probability of drainage by overflow, and in most cases it is certain that overflow did not occur. These individual ancient lakes, with some description of their terrace systems, are given in the following pages:

"*Abert Lake, Oregon.*—The highest terrace was measured by the writer as approximately 200 feet above the present Abert Lake.⁶ Below this are at least

⁴ Personal communication.

⁵ In the list of Bulletin 54 these basins are: Ralston Valley, Stonewall Flat, Sarcobatus Flat, Pahrump Valley, and Mesquite Valley, Nevada; Soda Lake, Rodriguez Lake, Harper Lake, Coyote Lake, Cronese Lake, and Langford Lake, California.

⁶ Russell (U. S. Geological Survey, Fourth Annual Report, 1884, p. 459) reports a terrace 250 to 300 feet higher, but the writer was unable to identify it.

seven major terraces at approximately 180, 150, 120, 90, 60, 25, and 15 feet. The 60-foot terrace is especially well developed. Below the 15-foot terrace there are at least five minor strands which appear to represent recent fluctuations of Abert Lake, since the vegetation which they carry differs markedly from that of the basin slopes in general.

"Alkali Lake, Oregon.—The highest terrace was measured by aneroid as 260 feet⁷ above the present bottom of the basin. Below this are at least four major terraces and perhaps five. About the present playa are recent strands at 1, 4, 8, and 15 feet.

"The Warner Basin, Oregon.—Aneroid measurement indicates that the highest terrace is about 200 feet above the present lakes. Below this are at least ten other terraces at elevations of approximately 190, 180, 170, 150, 120, 100, 80, 50, 30, and 15 feet. The 120-foot terrace is especially well marked and persistent. Below the 15-foot terrace are at least four recent strands.

"The Catlow Valley, Oregon.—Waring⁸ states that there are three well marked terraces, the highest over 75 feet above the present bottom of the valley.

"The Surprise Valley, California.—The highest terrace is estimated by the writer as about 350 feet above the present lakes. Below this are at least six others at about 330, 310, 280, 250, 180, and 150 feet. The 250-foot terrace is very well developed. There are at least three recent strands a few feet above the present lakes.

"The Alvord Valley, Oregon.—Waring⁹ reports four well marked terraces and two fainter ones, the highest over 100 feet above the present floor of the valley.

"The Madeline Basin, California.—Traces of a terrace system have been observed by the writer but have not been studied in detail.

"Dixie Valley, Nevada.—The highest terrace is 150 feet by aneroid above the present salt marsh. There is one below at about 40 feet, and perhaps one or two between. All terraces are poorly preserved and are represented by remnants only.

"The Columbus Basin, Nevada.—Conditions in this basin are complicated by considerable differences in level in different parts of the present playa and by the possibility of tilting since the lake period. At the south end of the playa the high terrace is 144 feet above the playa. At the north end the highest terrace found is 104 feet above the playa,¹⁰ the north end of the playa being, if anything, lower than the south end. The writer is uncertain whether this discrepancy is due to recent tilting or to the preservation at the two ends of the basin of fragments of different terraces. Below the high terrace are at least two others, the elevations of which at the south end of the basin are 85 and 55 feet.

"The Big Smoky Basin, Nevada.—A system of at least four terraces has been observed by the writer but not studied in detail. The highest appears to be about 50 feet above the present playa.

"Diamond Valley, Nevada.—Denizens of this valley report to the writer the

⁷ Waring gives this as 275 feet. U. S. Geological Survey, Water Supply Paper 220, 1908, p. 31.

⁸ U. S. Geological Survey, Water Supply Paper 231, 1909, p. 29.

⁹ Loc. cit.

¹⁰ Both elevations are from instrumental determinations by the writer and assistants.

existence of a system of well marked lake terraces. They have not been examined.

"Railroad Valley, Nevada.—By repeated aneroid measurement the highest terrace is 155 feet above the present playa. It is double, with the lower strand about 3 feet below the upper. There are well marked lower terraces at about 120, 105, and 65 feet, the last being especially well developed. Minor strands have been distinguished at about 95, 90, 85, 75, 60, and 50 feet.

"The Mono Basin, California.—Russell¹¹ reports a high terrace about 680 feet above the present lake and a complex system of lower terraces and strands which he does not describe in detail.

"The Salton Basin, California.—The phenomena in this basin appear to have been complicated by the occasional inflow of the Colorado River, with the consequent filling of the basin. The present Salton Sea is due to such an inflow, which was stopped artificially before the basin became full. There is one high terrace at about the level of overflow into the Gulf of California, and below this an extensive series of recessional strands.¹²

"The Otero Basin, New Mexico.—Huntington¹³ reports several high terraces between 200 and 280 feet above the present playa and three recent strands at 4, 20, and 60 feet, the 60-foot strand being somewhat doubtful.

"The Estancia Basin, New Mexico.—Meinzer¹⁴ reports a highest terrace almost 150 feet above the present playa and a complex system of lower terraces and strands, not described in detail.

"The Encino Basin, New Mexico.—Meinzer¹⁵ reports a high terrace at 60 feet above the present playa, with some evidence of a temporary lake stage still higher. No lower strands were found.

"Las Playas Valley, New Mexico.—Huntington¹⁶ reports at least one strand, the wave-bar which forms the Los Animas 'Dam.'"

A little study of the map shows that the basins described by Free as containing traces of ancient lakes are found in all parts of the area shaded black on figures 16 and 17. They do not occur in any region where the rainfall at present decreases during periods of many sun-spots. Much more important than this, however, is their striking evidence of the great complexity of the climatic history of this region during post-Glacial times. One or two of the oldest, most denuded strands may perhaps antedate the last Glacial period. The freshness of the others, however, and the fact that they do not appear to have been covered by water since they were formed indicates that they are of post-Glacial origin. The sharpness of the details of some of the smaller strands near the bottom indicates that they can not be of any great age—certainly not more than one or two thousand years, and perhaps only a few hundred. The

¹¹ U. S. Geological Survey, Eighth Annual Report, 1889, pp. 269-394.

¹² For details the reader is referred to MacDougal and others: *The Salton Sea*. Carnegie Institution Publication 193, 1914.

¹³ Carnegie Institution Publication 192, 1914, pp. 39-40.

¹⁴ U. S. Geological Survey, Water Supply Paper 275, 1911, pp. 19-23.

¹⁵ Loc. cit., pp. 77-78.

¹⁶ Loc. cit., p. 70.

remarkable series of strands in the Searles Valley, 22 in all, including the overflow strand, is most extraordinary. After this lake ceased to overflow it was for a long time the end member of the Owens Lake series. It received its water from a long, narrow, structural valley surrounded by mountains, which in some places rise 9,000 feet above its floor. It thus forms one of the best rain-gauges in America. The topographic relationships are such that each little variation in climate is recorded. Free suggests that the "very faint strands eighteen inches to two feet apart" in the lower 200 feet of the terrace series may "represent annual stages in the retreat of the ancient lakes." It seems more probable that they represent longer periods, such as the sun-spot cycle, or the 21-year cycle of Douglass and the 35-year cycle of Brückner. If this is so, the larger strands would represent periods from a few hundred to a thousand years in length, such as appear in the main fluctuations of the curves of tree growth in California. It is worth noting that the western edge of the Owens Valley drainage area is only from 25 to 35 miles from the districts where the big trees were measured. The general climatic fluctuations must be similar. A series of twenty or thirty cycles, such as those which are shown by the trees to have culminated in the fourteenth, tenth, and first centuries of our era, would bridge the gap between the last Glacial period and the present day. That the strands preserve a remarkably full record of the events which occurred during this interval seems highly probable. Whether the level of Lake Searles fell greatly after each strand was formed and then rose again to form the next lower strand, or whether it merely fell and then paused, can not yet be determined. In either case the interval between the Glacial period and the present time seems to have been filled with constant climatic pulsations whose general tendency has been toward less and less severity. The complexity of the changes indicates that we must appeal to some highly variable cause, such as the sun, rather than to causes, such as crustal deformation and changes in the composition of the atmosphere, which by their very nature act slowly and do not repeatedly reverse themselves at short intervals. The absence of any gap between the past and the present suggests that the same cause has been constantly operating.

THE INCLOSED LAKES OF ASIA

The lakes of the Old World furnish the same kind of evidence as those of the New. The fluctuations of the Caspian seem to be of the same sort as those of other lakes all the way from North Africa¹⁷ to Mongolia.¹⁸

¹⁷ See H. J. L. Beadnell: A desert oasis, pp. 110-122.

¹⁸ D. Carruthers: Unknown Mongolia, vol 2. Appendix.

One or two other lakes may be mentioned as samples of the intervening regions. Lake Buldur, in central Asia Minor, is surrounded by strands at elevations of 750, 460, 400, 100, and 35 feet, in addition to a minor strand at 8 or 10 feet. Lop-Nor, a lake in the eastern part of Chinese Turkestan, is also surrounded by six strands at elevations of 600, 300, 115, 35, 20, and 12 feet and by several minor ones at lower levels. The lake of Seistan, in southeastern Persia, not only presents two pronounced strands as evidence of recent fluctuations, but its deposits have been uplifted by recent earth movements, and show a series of apparently lacustrine beds alternating with beds which were apparently deposited under arid conditions. The date of these beds is uncertain; but they represent the last phase of the geological history of the region previous to recent volcanic outbursts, and seem to afford good evidence of a succession of climatic changes, numbering about 15, and closely analogous to those indicated in the Searles Basin. The long, deep, narrow valley of the Dead Sea is much like that of Owens Valley both structurally and climatically. It presents the same kind of favorable conditions for a full record of climatic changes. There we find old strands at elevations of 1430, 540, 430, 300, 250, 210, 170, 145, 115, 90, 70, 50, 40, 30, and 12 feet. It is scarcely necessary to point out the resemblance of this series of 15 strands to that of 22 in the Searles Basin. Inasmuch as some of the strands around the Dead Sea are double, the number of climatic fluctuations recorded at the two places is almost the same.¹⁹

It has sometimes been thought that strands such as are here described may have been the work of temporary lakes, due to the rapid melting of ice and snow which had accumulated during the Glacial period. This view has been advocated by Gale in a *Contribution to Economic Geology*,^{19a} published by the United States Geological Survey. He applies it specifically to such strands as are described by Free in the preceding quotation. According to this hypothesis, such lakes would have a very brief history, and would be only a transient phase of the glacial retreat due to increasing warmth rather than to variations in rainfall. That lakes of this sort were a feature of early post-Glacial time seems highly probable, but it is doubtful whether traces of them have yet been distinguished. The lakes which we are here considering do not seem to be of this origin for two reasons. In the first place, many of the strands are marked by broad, high beaches and ridges, or by lofty bluffs which could not have been

¹⁹ Further data on the strands of Asiatic lakes and the deposits of Seistan may be found in the following publications: *Explorations in Turkestan*, vol. 1; *The Pulse of Asia*; *Palestine and its Transformation*; and *Some Characteristics of the Glacial Period in Non-glaciated Regions*. *Bull. Geol. Soc. Am.*, vol. 18, 1907.

^{19a} *Bulletin* 540-N.: 1913, pp. 6-7.

formed unless the water had stood at approximately the same level for centuries. In the second place, the strands of the Dead Sea, to take the most striking example, could not possibly have been produced in this way, because the surrounding mountains do not rise high enough. No signs of glaciation have been described in any part of the area draining to that lake. Slight moraines are found on the west side of the Lebanon Mountains, but no part of this range drains to the Jordan River. There is no reason to think that there was any great accumulation of permanent snow, even at the height of the Glacial period, for no part of the drainage basin of the Jordan except the very top of Mount Hermon rises high enough. Even there the possible snow-covered area is not a tenth the size of the Dead Sea. The only feasible explanation of the strands of the Dead Sea seems to be changes of climate which express themselves chiefly in variations in the amount of precipitation. This conclusion applies to many other lakes, both in the Old World and the New.

THE CAUSES OF THE GLACIAL PERIOD

GENERAL DISCUSSION

We have now examined the little climatic changes which occur within the limits of the 11-year sun-spot cycle, the greater changes of historic times, and the still greater changes of the period between the culmination of the last Ice Age and the beginnings of history. We have seen that they all appear to be of the same type, although differing in degree, and that all are apparently explicable on the hypothesis of a shifting of climatic zones, such as now occurs on a small scale with each increase and decrease of sun-spots. This brings us face to face with the Glacial period. We must now examine that in respect to the three possible hypotheses of crustal deformation, change in the amount of CO_2 , and changes in the activity of the sun's surface. No serious student of geology would question that the deformation of the earth's crust and the resultant upheaval of mountains, elevation of continents, and formation of barriers in the ocean must have had most pronounced and long-continued effects on the climate. Such deformation must be regarded as one of the primary climatic factors. In the production of Glacial stages and epochs as distinguished from Glacial periods, however, there is little ground for the idea that it has been the chief factor, or even a factor of great importance. That the earth should have heaved up and down sufficiently to cause such vicissitudes, and yet that the evidence of it should be so weak and in many cases so strongly contradictory, is scarcely probable. A few geologists, to be sure, still cling to the idea that glaciation was due to an upheaval of the lands. They are forced, however, to reject most of the

evidence which points to alternate Glacial and inter-Glacial epochs. It seems safe to say that the vast majority of geologists agree that Glacial epochs have succeeded one another too rapidly to allow us to entertain the hypothesis that they are due primarily to crustal movements. Such movements probably prepared the way for the Glacial period by raising the continents to a great altitude, but their work ended at that point.

These considerations, together with what has already been said as to the meteorological and volcanic hypotheses, seem to limit our choice to the carbonic acid hypothesis and the solar hypothesis in one or the other of its forms. The carbonic acid hypothesis ranks as one of the great contributions to geology. Whether right or wrong, it has been remarkable for the extent to which it has stimulated investigation. The study of that hypothesis and a whole-hearted acceptance of it furnished one of the strongest of the stimuli which led to the present paper. The care with which it has been worked out and the admirable manner in which it has been presented will long serve as a model for geological work. I can not too strongly express my feeling of indebtedness to that hypothesis and of admiration for the way in which it has been framed.

THE CARBONIC ACID HYPOTHESIS

The cyclonic solar hypothesis and the carbonic acid hypothesis are not necessarily antagonistic. Both may contain large elements of truth, for one may explain climatic variations of very long duration, while the other may explain those of shorter period and quicker activity. Turning directly to the carbonic acid hypothesis, the first thing to be pointed out is that its supporters do not invoke it as an explanation of such brief changes as those which appear to have occurred during the past two or three thousand years. Even when it comes to Glacial stages they hesitate somewhat in its application. Others who are not so directly interested in it believe that it can not act quickly enough even to produce Glacial epochs. Its fundamental requirement is that changes shall be slow. A change in a given direction can be reversed only by a highly complicated rearrangement of the composition and movements of both the air and the ocean. Hundreds of thousands instead of mere hundreds of years are required to produce noteworthy effects. It is highly probable that changes in the carbonic acid content of the air are an important climatic factor. It scarcely seems possible that enormous amounts of CO_2 should at some periods be locked up in coal and limestone and at other periods be set free without altering the composition of the earth's atmosphere. Such alterations can scarcely fail to produce an effect on climate, especially through their alteration of the power of the atmosphere to hold

moisturè. This conclusion is based on actual observation. Different authorities may not agree as to the amount of effect produced by changes in CO_2 , but all appear to agree that there is some effect. When it comes to changes in ocean currents, however, the case is not so clear. Here the hypothesis is necessarily not based on direct observation, but on a highly complicated chain of reasoning. A periodic reversal of oceanic circulation appears to be the only way in which Glacial epochs can be explained according to the carbonic acid hypothesis, but the actual occurrence of any such reversal because of the action of CO_2 has never been demonstrated, even on a small scale. In the very nature of the case, any such demonstration is impossible, for the phenomenon must occur so slowly that many centuries would be required to detect it. In brief, the chief importance of CO_2 would seem to be in the production of climatic eras far longer than Glacial epochs. It may cause long periods of mild climate when equatorial conditions prevail far toward the poles, or equally long periods when the atmosphere is relatively free from CO_2 and the earth's temperature falls somewhat. This would mean that the influence of the composition of the atmosphere would vary with changes in the extent and elevation of the lands. In connection with the form of the solar hypothesis here presented we fully accept the idea that both deformation of the earth's crust and changes in the amount of carbonic acid in the atmosphere have been and will continue to be among the chief causes of climatic changes whose length is measured in hundreds of thousands or millions of years. They do not seem, however, to have been anything like so effective in producing changes measured in hundreds, or thousands, or even tens of thousands of years.

THE CYCLONIC SOLAR HYPOTHESIS

General discussion.—If we have reasoned correctly in our exclusion of other hypotheses, the only one which seems to be competent to explain Glacial epochs and the minor cycles shown by the California trees is the solar hypothesis. In its "caloric" form it does not seem to stand the test, for present changes of climate do not agree with changes in solar temperature. Moreover, from the point of view of the physicist, it seems beyond the bounds of probability that the sun's mean temperature should change sufficiently often and with sufficient rapidity to cause the observed terrestrial phenomena. The cyclonic form of the hypothesis seems to be free from such objections. We have already seen that there is a striking agreement between the changes of solar spots and variations in storms and winds. We have also seen that there is no inherent reason why the activity of the sun's surface, especially in its magnetic or electrical con-

ditions, may not have varied greatly and rapidly during past eras. It is now incumbent on us to test the matter in one more way. We must see what would happen if the present solar changes and the related terrestrial phenomena were to be greatly intensified.

Let us see how closely the earth's conditions would conform to those of a Glacial period if the disturbances of the sun's atmosphere which we know as sun-spots and the apparently associated disturbances of the earth's atmosphere became more intense than at present. Our assumption is simply that in their waning these various phenomena did not reach so low an ebb as at present, and that in their waxing they became decidedly more intense than today. Figures 7 and 12 may be taken as typical of the way in which the conditions of such a time would be different from those now prevalent. These maps show, in the first place, that the total number of storms, or rather the total storminess, for Kullmer's figures include both the number of storms and the length of their courses, would be greater in times of many sun-spots than in times of few. Then, according to our assumption, the degree of storminess during a Glacial period would be several times as great as now. The second thing that the maps show is that the distribution of storms would be different from what it now is. If the conditions thus indicated increased in the proportion demanded by our assumption, the result would apparently be the production of two main storm belts, both in America and Europe. In America one would be a boreal belt of great severity lying in southern Canada, or perhaps slightly farther north. If it were concentric with the magnetic pole, it would swing around over southern Greenland. It is quite possible, however, that during its course across the Atlantic Ocean it would be bent to the east and become the northern European belt. This, if it grew more intense than at present, would probably spread out so as to cover Scotland and much of Scandinavia, northern England, and the North Sea. The second, or subtropical belt, might have its most southerly point as far south as latitude 25° or 30° in America. Although less severe than the boreal belt, the storminess might be quite as great as in the present storm belt. Between the tropical and boreal storm belts would lie a region of comparatively few storms.

The double storm belt in America.—The idea of two distinct storm belts separated by a zone of few storms is so important that it requires further elaboration. Evidences of it can be seen in the present distribution of storms both in America and Europe. To begin with America, the main storm belt, as shown in figure 3, has its center in the northern United States and southern Canada. A southern belt, almost merged with the first, but nevertheless plainly discernible, has its center in more

southerly regions. It can be seen in Colorado, where a square crossed by 22.8 storm tracks per year lies south of two which are crossed by only 17.8 and 18.8. Just west of this Colorado square, and in the western part of the same State, a square crossed by 13.2 tracks lies south of one crossed by 12.8 and of another crossed by 12. Still more to the northwest we have 9.0 south of 6.9 and 7.8. In times of numerous sun-spots there seems to be an unmistakable tendency for this incipient southern storm belt to become more highly developed. A study of figure 7 and of the others of the same kind proves that this must be the case. In times of many spots storminess decreases in the central United States and increases on either side. If this process goes far enough, we are bound to have an area of actual deficiency of storms in the center and two storm belts on either side. The case is like that of a heap of sand from which sand is shoveled to either side. No matter how high the central heap may be, its level will ultimately fall below that of the heaps on either side, provided the shoveling be continued long enough.

In order to make the matter as concrete as possible, I have prepared the diagrams shown in figure 19. They represent the number of storm tracks in the given longitudes under four different conditions. The figures at the bottom represent latitudes; the height of each curve shows the number of storms. Each curve begins at zero in a latitude sufficiently far north so that no storm centers actually pass over it. Going south—that is, toward the right in the diagrams—the number of storms rises to a maximum and then decreases with more or less regularity. The first set of curves shows the conditions in longitude 60° to 65° west, the next in longitude 70° to 75° west, and so on to 120° to 125° west. In each set there are four curves. The upper, marked "Min," shows the distribution of storminess at times of minimum sun-spots according to figure 7. The next line, marked "Av," shows the average distribution for 30 years according to figure 3. The third line shows the conditions at times of maximum spots according to figure 7. Finally, the lower line represents the conditions which would prevail if the conditions which now exist during times of maximum sun-spots were magnified sixfold. This does not mean that the actual number of storms has been multiplied by six, but that the departures have been so multiplied. In other words, if at one particular point the curve marked "Max" shows that the number of storms at times of maximum spots now averages two in excess of the average for all the years for which data are available, this excess has been multiplied by six and becomes 12 in the "Max. $\times$ 6" curve. Thus the average number of storms for all years may be 20. During the nine

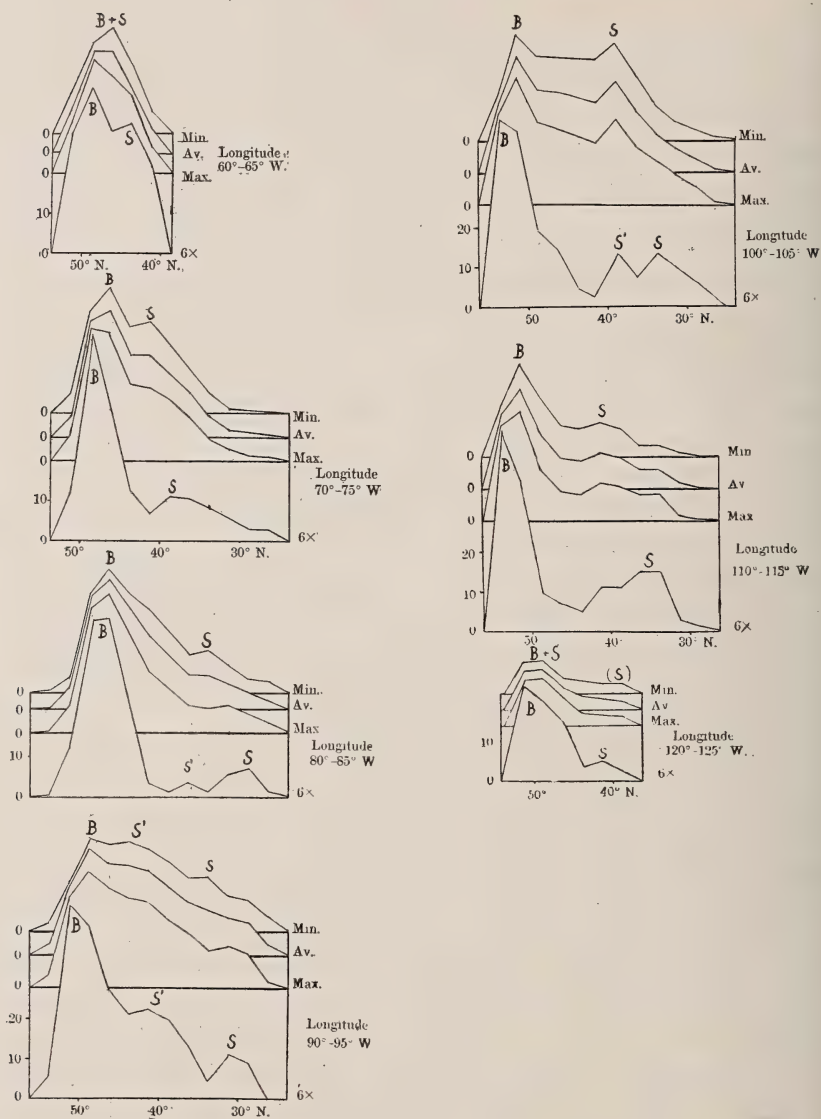


FIGURE 19—The double Storm Belt of the United States

Av. = Average number of storm centers during the 30 years from 1883 to 1912

Mn. = Average number of storm centers during 12 years of minimum spots

Mx. = Average number of storm centers during 9 years of maximum spots

6x = Average number of storm centers if the departure of Mx. from Av. were increased sixfold

B = Boreal storm belt

S = Subtropical storm belt

The figures on the left of each diagram indicate the scale on which the number of storm tracks is plotted

years of maxima since 1877 the average may have been 21. If we suppose that the conditions which accompany sun-spots are magnified six-fold, the number of storms would be 26, and this is the figure used in plotting the lower curves.

If we examine the various groups of curves, we see that they all agree in certain important features. Beginning with the curves for longitude 60° to 65° , we see that at times of minimum spots, as represented by the upper curve, there is a regular increase of storms as one approaches latitude 45° to 47° . The place where the storms are most numerous is indicated by the letters B + S. In the next curve, the average for all years, the high point, B + S becomes flattened. In the third curve, representing conditions as they now exist at times of many sun-spots, the region of greatest storminess has moved two or three degrees north of its location in the minimum curve, while on the other side, southward, there has developed a somewhat prominent angle. Finally, in the lower curve we see that if the conditions which accompany many sun-spots at the present time should be exaggerated sixfold, there would be a sharply defined maximum of storminess between latitudes $47^{\circ} 30'$ and 50° and another maximum of less proportions between latitude $42^{\circ} 30'$ and 45° . Turning to the next set of curves for longitude 70° to 75° , we see the same conditions repeated. The only essential difference is that here we have a hint of a double maximum even in the curves for the actual conditions as they exist today. The same is true of the curves for longitude 80° to 85° and 90° to 95° . The latter presents some slight irregularities which seem to be related to the curious little tongue which projects southward from the main area of northern increase of storminess in figure 7 and elsewhere. In the groups of curves for longitudes 100° to 105° and 110° to 115° , especially the former, the two belts of storms stand out distinctly even in the upper curves. Finally, in the last group the conditions of the first are quite closely repeated.

Summing up the whole matter, we see that except for the extreme borders of the continent the curves of present storminess all show not only the main crest of what we have termed the boreal storm belt, which is indicated by the letter B, but also some faint indications of the smaller subtropical belt, which is indicated by the letter S. If we turn to the lower line in each group, we see that in all cases, without exception, there are two distinct crests. Invariably also there is a tendency for these two crests to separate from one another as the conditions which accompany maximum sun-spots become intensified. The boreal crest generally moves only 2 or 3 degrees from its present position, while the subtropical

crest may move twice as much. Between the two the number of storms decreases until there comes to be an area where storminess is slight.

The glacial storm belts of Europe.—In Europe the double character of the storm belt at the present time is much more evident than in America, as may be seen in figure 4. The effect of changes in the belts in accordance with changes in the number of sun-spots, however, is by no means so clear as in America, but will probably become so when we have figures for the last two sun-spot cycles. Meanwhile we can merely point out certain features which appear in figure 12 and whose main outlines may possibly be permanent characteristics when sun-spots are numerous. It must be remembered, however, that we here have only a single sun-spot maximum compared with two minima, and that the figures are not so reliable as in America. If we had more abundant data many of the minor features would probably disappear. In general the maps indicate that during times of many sun-spots there is a deficiency of storms over the Icelandic region and also in Finland, but this latter is of doubtful importance. A belt of increased storminess extends from Scotland up to Scandinavia, down into Germany and eastward. With more abundant data this would probably spread out so as to cover all of Scandinavia. In England we find a belt of deficiency which extends eastward into northern France, and from there down the Danube Valley and into Austria. In figure 10 this area goes directly across the Alps to the head of the Adriatic Sea. In figure 11 it goes north of the Alps and is much enlarged in Hungary, whence it continues east to the Crimea. What appears to be the same as the Crimean area is apparent on a much reduced scale in the other map, where we have a decline in the rate of increase northeast of the Crimea, but not actually a deficiency. Just what would happen if the conditions illustrated in the European maps should become much intensified it is as yet hard to say, but presumably there would be a stormy area in the northwest and north, an area of deficiency in the west and center, and again an area of excess in the southeast. The essential point is that both in America and in Europe we have evidence that real changes are in progress in harmony with the sun-spot cycles, and that if these should become intensified the distribution of storms would apparently correspond with what presumably occurred during the Glacial period.

The effect of the glacial storm belts on temperature and precipitation.—So much for the location of storms according to the cyclonic hypothesis. Now for the distribution of temperature. With high sun-spot frequency the temperature of the torrid zone appears to diminish. This

seems to be well established and we have discussed its probable mechanism. According to our assumption, the temperature would merely be lowered still more than is now the case at times of sun-spot maxima. In the storm belts the temperature would be lower than at present, just as is now the case at such times, but the amount of lowering would not be so great as within the tropics. In polar regions the temperature might remain about the same as now. The facts are not yet well enough known to give any certainty.

Having indicated the conditions that would prevail according to our assumption, let us now set the mechanism in motion. In America, and to a less extent in Europe, the more equatorial of the two belts of storms would keep the air of the torrid zone in active motion. Tropical hurricanes would be more numerous than now, and storms of the eastward-moving type; characteristic of the temperate zone, would abound somewhat to the north of the region of hurricanes. The active upward movement of the air in the storm centers would produce an abundance of rain and would carry away an abundance of heat. New air would be continually brought from the lands to the oceans and back again, so that evaporation would increase, even though the temperature were lower than now. Thus two conditions would tend to promote the accumulation of snow and the formation of glaciers among the mountains. In the first place there would be more precipitation than now, and in the second place there would be less melting. Such conditions would prevail as far north as the center of the subtropical storm belt. Beyond this would lie the median belt of decreased storminess. The temperature there would apparently be lower than now, but the degree of lowering would presumably not be so great as within the tropics. Storms would occur in summer when the subtropical storm belt moved north, and in winter when the boreal belt moved south. Yet the actual amount of precipitation would probably, and indeed almost certainly, be less than at present.

North of the subarid zone would lie the great boreal storm belt. Farther north than now and more intense it would whirl its storms around the edge of the highlands of Labrador and Scandinavia. It would not only cause precipitation, but also constant cloudiness. Thus the snows of winter would have scant chance to melt. In the colder districts they would gradually accumulate, and as the storms grew more numerous great areas of permanent snow would appear, and continental glaciers would at length begin to creep forth. In their cold centers areas of high pressure would doubtless exist like those which now prevail in Antarctica and Greenland. The presence of these centers would in itself increase

the severity of the winds, for it would establish high barometric gradients, down which the winds would sweep viciously. The growth of the glacial area would cause the region of high pressure also to increase in size, and thus the boreal storm belt would be pushed equatorward and would maintain its position along the ice-front. As long as the sun maintained its high degree of activity the storms would continue and the glaciers would grow. Then when the solar disturbances ceased the terrestrial storms would also decrease in severity, the two cyclonic belts of each hemisphere would tend to merge, precipitation and cloudiness would decrease, and the sun would have an opportunity to melt the accumulated ice.

The glacial precipitation of the Alps.—The severest test and the greatest confirmation of any hypothesis is found in the extent to which it explains highly specialized facts which were not known or were not considered when it was framed. Several such facts appear at once as soon as our cyclonic hypothesis is applied to the glaciation of past times. They are not in any respect new, but were not thought of in framing the hypothesis. They came to mind only when the line of reasoning which has just been followed had been brought to the present point. Then they stood out so clearly that what I am about to say will probably be only a repetition of what has already occurred to most readers. Therein lies their importance. A knowledge of the hypothesis here discussed would lead to the expectation that certain peculiar phenomena prevailed during times of glaciation. When we inspect the history of Glacial periods as worked out by geologists those phenomena stand out as among the most difficult to explain. The first is Penck's conclusion that in the Alps, but not necessarily elsewhere, the snowfall during the Glacial period can not have been appreciably heavier than now. The upper surface of the ancient glaciers at their point of origin never rose higher than the present surface. Hence he infers that there can never have been more snow than today, and that the expansion of the Alpine glaciers must have been due entirely to the lowering of the temperature. A glance at figure 10 shows that during that particular period of maximum sun-spots the amount of storminess over the Alps did not increase nearly so much as in many other places. In fact it remained almost stationary. In figure 11 we see that the storminess of the Alps increased somewhat, but the area of increase is small and its intensity is not great. There is a strong probability that if the general conditions which prevail at times of sun-spot maxima should greatly increase, the Alpine area of excess would either be absorbed in the surrounding area of deficiency or would remain nearly neutral—that is, not appreciably different from what it is today. This

would conform exactly with Penck's conclusion. The temperature would fall because of the draining away of the warmth of the lower atmosphere. This in itself would tend to decrease precipitation somewhat. A slight increase in storminess would be needed in order to balance this. Thus if the Alps had somewhat more storminess than now, but were surrounded



FIGURE 20.—*The Distribution of Loess. Its Relation to Quaternary Glaciation and to present Deserts and subarid Regions.* (After De Martonne)

(Reproduced from Fig. 310, p. 664, in De Martonne's *Traité de Géographie Physique*)

by an area of decrease, we should get the conditions which seem actually to have existed.

The distribution of loess.—A more striking case than that of the Alps is found in the distribution of loess. This is illustrated in figure 20, which is taken from De Martonne's *Traité de Géographie Physique*. As the map plainly shows, there are two chief types of loess. One consists of deposits on the leeward side of modern deserts. In places such as

northern China this material has been accumulating for ages and is still in rapid process of deposition. There can be no question as to its origin. I have myself seen loess blown from the Takla Makan Desert of the Tarim Basin and deposited on the northern flank of the Kwen-lun Mountains, 8,000 feet above the desert and 60 miles away. Standing on the mountain side in the early morning, we could see the desert clearly. Gradually it became obscured by dust, under the influence of a strong north wind. By afternoon the dust reached us. It fell so thickly that our writing paper became covered with it and had to be brushed every few minutes to prevent the pen from blotting. Conditions like this seem to be the only ones where any great quantity of loess is being deposited at the present time. Nevertheless, as is seen in figure 20, there are large areas where vast deposits were formed during Pleistocene times, but which now are not in such relation to deserts that they could possibly receive dust from them. A belt of this sort extends across the southern borders of Siberia between 45° and 50° north. Its westward extension passes through southern Russia, across Roumania and Hungary, up the Danube, and over into France. There it extends as far as Brittany and even over into the extreme south of England. Other small areas of loess lie in southern France near the mouth of the Rhone and in southern Spain. In America similar conditions prevail. The central part of the United States, especially along the Missouri, Mississippi, and Ohio rivers, contains abundant deposits of loess dating from the Glacial period. Thus, although as a general rule it appears that in modern times all known deposition of loess on a large scale is due to winds blowing from deserts, yet in ancient—that is, Pleistocene—times the deposition of loess seems to have been closely associated with glaciation and to have taken place chiefly not far from the front of the ice. The ice indicates heavy precipitation or else low temperature and the consequent absence of rapid melting and evaporation. The loess indicates lack of precipitation or else high temperature and extremely rapid evaporation.

The peculiar juxtaposition of these two phenomena has been one of the most puzzling features of glacial geology. It has led to the theory of a twofold origin of loess. Geologists have been forced to conclude that this material can originate not only in deserts, but also in the outwash plains which lie in front of glaciers. It has been supposed that during the Pleistocene summer the ice melted rapidly and great streams flowed from its front. The streams must have spread into many channels and flooded large areas. During the winter, when melting ceased, the streams presumably diminished or even disappeared in many cases. Then the

winds had free play, and are supposed to have picked up the fine material deposited by the water and to have piled it in great drifts. The chief difficulty with this theory is that we do not now see it in operation except in a few insignificant cases. There are many places where dry flood-plains are gathering grounds for wind-blown dust, but practically all the cases where this gives rise to loess are in deserts and not at the front of glaciers.

The cyclonic form of the solar hypothesis seems to afford an adequate explanation of the peculiar phenomena which have just been described. By its very nature the hypothesis demands that belts of excessive storminess and precipitation should lie close to belts of diminished storminess and of aridity. If these did not occur the theory would be untenable. A comparison of figure 20 with figures 11, 12, and 7 shows that in both Europe and America the areas where storminess decreases at times of sun-spot maxima are the areas where loess was abundantly deposited during the Glacial period. Manifestly, if the decrease in storminess which is shown in central Europe and in the central United States in figures 11 and 7 should become intensified, those regions would become deserts and be the sort of places where loess could originate. Just north of the deserts—that is, not far from the ice-sheet—would lie the main track of storms. In summer, when storms were most frequent, their courses would lie farthest north, just as is now the case, and the centers would presumably often pass within the limits of the ice. Therefore in the area fronting the ice the prevailing winds would be from a southerly direction, but ranging well toward both the east and the west. They would be strong winds, for under the assumed conditions of our hypothesis the barometric gradients would be steep and the storms would be more severe than at present. The constant indraft of air from the deserts would bring with it great amounts of dust, which would be deposited in the regions where the glacial streams were depositing their outwash. The net result would be either the accumulation of pure wind-blown loess in areas not subject to inundation by glacial streams, or the deposition of an intermixture of loess and fluvio-glacial materials in the areas where the streams from the ice were laying down their burdens. The agreement of this condition with that which we know to have been the case during the Glacial epoch scarcely needs to be pointed out.

PERMIAN GLACIATION

GENERAL DISCUSSION

The last test to which we shall subject our theory is that of the peculiar condition of Permian glaciation. This, still less than the snowfall of the Alps and the loess of Eurasia and America, was not even remotely considered until the cyclonic hypothesis had reached its present form. Perhaps the most striking characteristic of Permian times was glaciation between 20° and 40° south of the present equator and to a less extent in the same latitudes north of the equator. The extent of the evidences of glaciation is sufficient to imply the existence of considerable bodies of land. The actual regions where the ice laid down its burden were in many cases at or near sealevel. This, however, indicates nothing as to the conditions far back where the glaciers took their origin. At the present time glaciation is universally associated with mountains or with regions such as Greenland and Antarctica, which are presumably high plateaus. In the Pleistocene glacial period the great areas of the accumulation of ice were all of considerable elevation. Therefore, we seem to be led to the conclusion that during Permian times considerable areas of high land or mountains must have existed in latitudes 20° to 40° , where they served as a gathering ground for great quantities of ice. Even with this assumption, however, the peculiar location of Permian glaciation has been an even greater puzzle than the juxtaposition of glaciers and loess in Pleistocene times. The problem has been so difficult that some of the best geologists have thought that it might indicate a change in the location of the earth's poles. Others have endeavored to explain it by a complete readjustment of oceanic and atmospheric circulation. Such a readjustment must certainly have taken place, no matter what hypothesis we accept in explanation of it, but its mode of occurrence would vary according to whether it was due to crustal deformation, changes in the composition of the atmosphere, or changes in the cyclonic movements of the air.

According to the cyclonic hypothesis, the Permian period was a time when the activity of the sun was even greater than during the Pleistocene glacial period. This, as we have seen, would involve the formation of a storm belt in subtropical latitudes, together with an increase of tropical hurricanes in subequatorial regions. Both of these types of cyclonic activity would involve a rapid upward movement of the air, which would be at its greatest intensity in a broad subtropical belt centering 25° or 30° from the equator on either side. Under such conditions two factors,

as we have already seen, would tend toward glaciation. One would be a pronounced increase of snowfall on the mountains and the other the general lowering of the temperature because of the great amount of heat carried upward by the storms. Conditions would apparently resemble those which would prevail in New Zealand if the temperature should become somewhat lower than now and the snowy precipitation on the mountains should increase. At the present time the glaciers of New Zealand descend almost to sealevel. For instance, the Aorangi glaciers push their way down into the forests as low as 400 feet above the sea. With an increase in snowfall and a slight lowering of temperature, these glaciers would descend still lower. They would coalesce with one another and might spread out over a considerable area of land at approximately sea-level. In order to get such conditions during the Permian era, the only requirements seem to be that the phenomena which now prevail at times of maximum sun-spots should become even more intensified than we have assumed to be the case in Pleistocene times.

THE EFFECT OF PRECIPITATION ON TEMPERATURE

At this point it is necessary to consider two points which may be raised as objections to the cyclonic hypothesis. One of these is the liberation of latent heat by reason of increased precipitation, which might cause the temperature to be raised instead of lowered in the subtropical storm belts. The other is the blanketing effect of an atmosphere full of moisture and clouds. The effect of the first can easily be determined. The heat required for the evaporation of a given amount of water is exactly equal to the heat liberated by the condensation of the vapor thus produced. If the circulation of the air in subtropical latitudes were much more rapid in Permian times than at present, a constant supply of unsaturated air would be brought to the equatorial areas of chief evaporation. This air would take up moisture and in so doing would lose heat. It would then be carried upward, partly in equatorial regions and still more in the subtropical storm belt. At an altitude of a few thousand feet condensation would take place and the latent heat would be liberated. This would warm the air, and the amount of warming would be essentially the same as the amount of cooling which took place when the moisture was first evaporated. The effect on the earth's surface, however, would be to produce cooling, for the heat would be taken away from the air at low levels and would be released at the high level of the clouds. Moreover, when air is warmed by the condensation of moisture and the formation of clouds, it of course expands, and hence tends to rise more rapidly than before. Therefore its heat is carried to levels above those of the clouds,

and is largely lost, so far as any effect on the earth's surface is concerned. Hence it appears that the greater the amount of evaporation from the ocean, the greater will be the amount of heat carried to high levels and the greater will be the cooling effect on the earth's surface.

THE EFFECT OF A PERMIAN CLOUD BLANKET IN LOW LATITUDES

We must now consider the extent to which an increase in atmospheric moisture and cloudiness in subtropical and equatorial regions would exercise a blanketing effect which might neutralize the cooling effect described in the last paragraph. As every one knows, on clear nights frost is much more probable than on cloudy nights. When the air is full of moisture, and especially when it is cloudy, the earth's heat is not radiated away so fast as when the air is clear and dry. The universality of this phenomenon raises the question whether under conditions such as we have postulated during Permian times the great abundance of clouds might not actually cause the temperature of the earth's surface to rise rather than fall. To put the matter concretely, we must find the relation between two types of processes. On the one hand, we have the cooling processes. These are three in number: First, the convective carrying away of heat from the earth's surface by reason of rapid cyclonic circulation; second, the carrying away of heat because of rapid evaporation, and third, the actual loss of heat which would arise from the reflection of the sun's rays from the upper surface of the clouds. This last factor has not hitherto been mentioned, but it plays an important part. Water, as is well known, possesses a high reflective power, and the same is true of clouds. If any part of the earth's surface is shrouded with clouds, there must be a corresponding absolute loss in the amount of heat received from the sun.

In opposition to the three cooling processes there seems to be only one heating process which would play any important part under the conditions of the cyclonic hypothesis. Inasmuch as the wave length of sunlight is very short, solar energy, unless it is reflected from the surface of clouds or of other reflecting media, is able to pass through masses of vapor without being absorbed to any great extent. On reaching the earth, however, it is converted into heat and is sent out from the earth's surface in this form. The wave length of heat is great. Hence when the waves come into contact with vapor they can not easily pass through it, but are largely absorbed. For this reason clouds prevent the earth from becoming cool.

Our problem is to determine whether, under the conditions of our hypothesis, the loss of heat in Permian times on account of increased

convection, evaporation, and reflection exceeded the gain due to the blanketing effect of increased cloudiness. This can be tested either mathematically or empirically. Both methods meet with many complications. Doubtless the mathematical method will in the end prove the most reliable, but with our present scanty knowledge it requires a great number of assumptions which expose it to constant error. Moreover, the process of calculation is so intricate that the layman is almost sure to make mistakes. Therefore it seems wiser to adhere to the method which prevails throughout this paper—that is, let us discover what is happening today and then ascertain what would have happened if the same thing had occurred on a larger scale in the past.

THE BLANKETING EFFECT OF CLOUDS AT PRESENT

In order to find the present relation of clouds to temperature, I have made use of four charts in Bartholomew's Meteorological Atlas. Two show the mean cloudiness of the world in January and July. The cloudiness is expressed in tenths of the sky which are obscured. The other two charts are those of isanomalies of temperature in January and July. These indicate the extent to which the temperature departs from what would naturally be expected in any given place at the particular time in question. For instance, if there were no winds and ocean currents, the west coast of Ireland would be as cold as the east coast of Labrador. As a matter of fact, in January Ireland is more than 30° F. warmer than would be expected in its latitude, while the east coast of Labrador is 10° F. colder than would be expected. These figures constitute the anomalies for the respective regions during January. The parts of the earth more than 30° from the equator are subject to extreme anomalies, partly because of the great size of the continents and partly because of the ocean currents. Therefore the present investigation has been restricted to the area within 30° of the equator. This is the more appropriate, since, according to the assumptions of our hypothesis, it is chiefly there that storminess appears to have increased during Permian times.

In the charts of cloudiness and temperature anomalies use has been made of the 126 points where the equator and the parallels of 10° , 20° , and 30° north and south intersect the meridians of 0° , 20° , and 40° , and so on at intervals of 20° around the world. For each point the anomaly and the cloudiness in January and July have been taken, and the figures have been combined so as to show whether increased cloudiness is accompanied by a rise or fall of temperature. Three different methods have been pursued. In the first place all the points have been divided into groups on the basis of their anomaly. The first group, A in Table 7,

TABLE 7

Cloudiness at Places having various Temperature Anomalies between 30° south and 30° north for the Months of January and July

Temperature anomaly.	Whole world.		Land.		Ocean.	
	Basis.	Average cloudiness.	Basis.	Average cloudiness.	Basis.	Average cloudiness.
A, -10° F. or more.	5	5.1	....	.....	4	5.0
B, -5° to -9.9°	25	4.68	....	.....	23	4.63
C, -2.6° to -4.9° ...	31	5.24	6*	4.58	28	5.39
D, -1.0° to -2.5° ...	54	4.72	16*	3.63	38	5.18
E, -0.9° to 0.9°	26	5.06	5	5.0	21	5.07
F, 1.0° to 2.5°	54	4.99	18	4.67	36	5.15
G, 2.6° to 4.9°	33	4.80	18	4.39	15	5.30
H, 5.0° to 9.9°	16	4.56	12	4.58	5†	4.90†
I, 10° or more.....	8	3.19	7	2.71	....	.....

* A, B, and C. † H and I.

includes places showing an anomaly of -10° F. or more. The second, B, includes places showing an anomaly of -9.9° to -5.0° , the third from -4.9° to -2.6° , and so on up to a plus anomaly of 10° or more. The results are shown in Table 7 and figure 21. Taking oceans and lands together, it appears that in the small number of cases included in group A, where the temperature falls most greatly below what would be expected, the average cloudiness is 5.1° F., which means that the sky is covered with clouds a trifle more than half of the time. In the next three groups the cloudiness jumps back and forth, as is seen in the middle

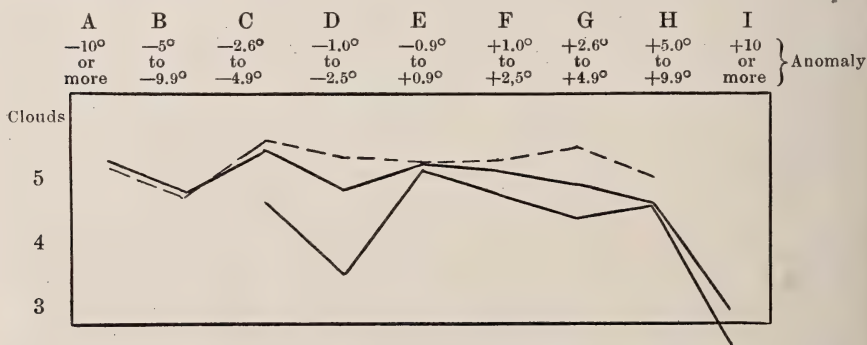


FIGURE 21.—Cloudiness in Regions having various Temperature Anomalies, according to Table 7

Upper dash line = water alone
 Upper solid line = land and water
 Lower solid line = land alone

line of figure 21, but never departs far from 5. Then, beginning with group E, which includes all places having an anomaly of less than 1° , we see that there is a steady decrease in cloudiness as the anomaly becomes greater in the plus direction. In other words, where the temperature is lower than would be expected, there is a fairly high degree of cloudiness, whereas where the temperature is higher than would be expected there is relatively little cloudiness. This looks as if there were a distinct relation between unusually high anomaly and the absence of clouds. Over the ocean this relationship does not seem to be of any importance, as appears in the upper curve of figure 21. Over the lands, however, as appears in the lower curve, it is distinct, although a marked irregularity occurs at D, and there are almost no data for groups A and B. Taken as a whole, the curves are not very conclusive except in one point. There can be no question that over the lands—that is, in the places where the climate depends most closely on the sun—an extreme excess of heat is found where the cloudiness is least.

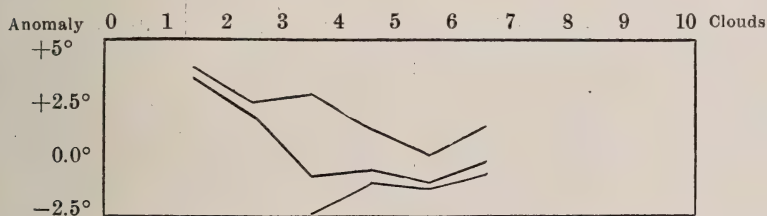


FIGURE 22.—Temperature Anomalies for various Degrees of Cloudiness, according to Table 8

Upper line = land areas
Lower line = oceanic areas
Middle line = oceans and land combined

Let us test the matter in another way. In Table 8 our different points of observation are grouped according to the degree of cloudiness instead of according to the anomaly, as in Table 7. The first group includes all points having a cloudiness of 2 or less, the next those having a cloudiness of from 2 to 3, and so on up to those having from 6 to 7. The meaning of Table 8 can readily be grasped from figure 22. In the upper line it is evident that over the lands an increase of cloudiness is accompanied by a fairly steady decline in the anomaly. Where the cloudiness is between 1 and 2 the temperature is on an average 3.89° F. higher than would be expected. Where the cloudiness rises to 4 or more, on the other hand, the anomaly drops to plus 1, or even to 0. The oceans, on the contrary, show a slight tendency in the opposite direction. They are of far less importance than the lands, however, for their temperature

depends largely on the transportation of heat by ocean currents. Thus an anomaly which actually arises in a sunny region may be transported toward a cloudy region, and may there be concentrated so that it appears more important than at its place of origin. Indeed, the place of origin may actually be cooled by the rapid removal of heat. If we take the lands alone we find that the method employed in Table 8 and figure 22 points strongly toward the conclusion that the presence of clouds is associated with relatively low temperature at the earth's surface.

TABLE 8

Temperature Anomalies at Places having various Degrees of Cloudiness between Latitudes 30° south and 30° north for the Months of January and July

Degree of cloudiness.	Entire area.		Land area.		Oceanic area.	
	Basis.	Average anomaly.	Basis.	Average anomaly.	Basis.	Average anomaly.
0—1	3	(+5.33°)	3	(+5.33°)	0	.....
1.1—2.0	16	+3.33°	14	+3.89°	2	.....
2.1—3.0	16	+1.78°	13	+2.35°	3	(—0.67°)
3.1—4.0	42	—0.82°	12	+3.17°	30	—2.42°
4.1—5.0	75	—0.52°	18	+1.11°	57	—1.04°
5.1—6.0	58	—1.03°	12	±0.00°	46	—1.29°
6.1—7.0	38	—0.14°	10	+1.40°	28	—0.70°
7.1—8.0	4	(+4.9°)	3	(+4.66°)	1	.....

In the two preceding methods we have compared different parts of the earth with one another, and hence have been liable to error because of the great variety of relief, currents, winds, and other physical characteristics which prevail in one region or another. Let us now compare the conditions of each region at different times of the year. The results appear in Table 9. Among the 126 points used in our calculations 110 show a distinct change of cloudiness from January to July. In 59 cases the cloudiness decreases and in 51 it increases. Over the lands the average temperature is higher in July than in January, no matter whether the cloudiness is greater or less, while over the oceans the reverse is true. This, however, does not prevent us from testing the matter, for we can determine whether the cloudy places have a greater or less increase or decrease of temperature than do the ones with less clouds. Testing the matter in this way, we find that on an average the land stations where the cloudiness is greater in July than in January have an anomaly +1.33° F. greater in July than in January. On the other hand, the stations where the cloudiness is less in July than in January have an

anomaly $+1.92^{\circ}$ F. græater in the later month than in the earlier. The difference between these two figures is 0.59° F. If there were no increase in cloudiness in the first group of places the temperature would apparently rise to this extent—that is, 0.59° —higher than it actually does. In the oceanic areas the result is similar. Here the places which show an increase of cloudiness show a lowering of their anomaly to the extent of -1.49° , while those which have a decrease of cloudiness show a lowering

TABLE 9

Comparison of Changes of Cloudiness from January to July with Changes of Temperature Anomaly from January to July, between 30° south and 30° north

	Area in per cent of whole.	Average change of cloudiness from January to July.	Average change of anomaly from January to July.
Whole world:			
Regions with same cloudiness in January and July	12.0	0.00	$+2.59^{\circ}$
Regions with less cloudiness in January than in July.....	40.0	$+1.37$	-0.06°
Regions with more cloudiness in January than in July.....	48.0	-1.61	-0.35°
Land:			
Regions with less cloudiness in January than in July.....	10.2	-1.35	$+1.92^{\circ}$
Regions with more cloudiness in January than in July.....	19.4	$+1.96$	$+1.33^{\circ}$
Ocean:			
Regions with less cloudiness in January than in July.....	30.0	-1.38	-0.74°
Regions with more cloudiness in January than in July.....	28.4	$+1.28$	-1.49°

Average difference due to clouds, 0.70° .

of their anomaly only to the extent of -0.74° F. The difference is 0.75° F. The meaning of these facts is that where cloudiness increases the temperature is lower than it would otherwise be to the extent of 0.75° F. over the oceans and 0.59° F. over the lands. Making due allowance for the difference in the area of the land and the sea, this gives us an average decrease of temperature amounting to 0.70° F. The amount by which the cloudiness changes on both land and sea is on an average about 1.5, but since the change is plus in one case and minus in the other



FIGURE 23.—Glaciation and the Distribution of Land (unshaded) and Sea (shaded) during the Permian Era. (After Schuchert)

The direction in which the ice moved is indicated by arrows

the difference between the extremes is 3. Hence an increase of 4.2 in cloudiness would apparently be accompanied by a fall of 1° F. in temperature.

The preceding discussion seems to show that at the present time the net effect of an increase in cloudiness, however it may be produced, is a decline of temperature. It does not seem probable that the reverse is true, and that the greater cloudiness is due to a lower temperature. If this were the case it would involve a seasonal change in the amount of heat supplied to the earth, and this change would have to be greater over the lands than over the sea. Hence we conclude that the increased body of clouds actually reflects so much sunlight that the earth's surface becomes cooler in spite of the fact that the clouds hinder the radiation of heat away from the earth. The amount of cooling thus occasioned is not large. Even under the circumstances which we have postulated for the Permian ice age, it would amount to only a degree or two. It should be noted, however, that it would apparently be greater in proportion to the amount of land. This would give it a maximum importance in Permian times. Moreover, it would cooperate with much larger diminutions of temperature arising from increased convection and evaporation. The chief importance of the matter lies in the fact that it shows that at present the increase of cloudiness, which is the only important positive factor in raising the temperature of the earth's surface under our assumed glacial conditions, is not able to counteract the factors of an opposite character which diminish the temperature. This, then, seems to support the idea that in Permian times excessive convection, evaporation, and refraction may have lowered the temperature of subtropical regions to such a point that the heavy precipitation was able to produce glaciers which descended to low levels.

THE PERMIAN DESERT IN THE NORTH

Leaving now the equatorial and subtropical regions, let us consider the probable conditions which may have existed elsewhere in Permian times according to the cyclonic hypothesis. Poleward of the two subtropical storm belts would lie the median zones of diminished storminess and precipitation. These would presumably become intensified. They would be not merely arid regions, such as appear to have occupied this belt during the Pleistocene glaciation, but would become vast deserts. There would be especial reason for expecting this, if the lands between 40° and 70° from the equator were very broadly developed, so that the oceans were greatly diminished in size. During the Permian period this condition

appears to have prevailed in the northern hemisphere. The probable extent of the lands of that time and their transversal arrangement as contrasted with the longitudinal arrangement of the present is illustrated in figure 23, which is here reproduced from Professor Schuchert's chapter in "The Climatic Factor." The subtropical storm belt, according to the cyclonic hypothesis, presumably extended essentially along the line of oceans between latitude 20° and 40° , so that the winds which blew in toward the cyclonic centers were apparently well supplied with moisture, which would help to account for glaciation in low latitudes. Farther north the great belt of deserts would be very poorly supplied with water because of the lack of oceans. In this region we find one of the most striking characteristics of Permian times, namely, a vast accumulation of red beds, saline formations, and other evidences of aridity. This "rote nordland," as Walther has called it, is full of unfossiliferous, arid deposits, and its condition has hitherto been another of the puzzling features of the geological middle ages. Similar conditions have prevailed at earlier times, such as the Devonian, and the explanation which applies to the Permian is equally applicable to other periods.

Finally, in the far north our assumed great increase in the activity of sun-spots would cause another belt of pronounced storminess, just as during the Pleistocene. For two reasons, however, the effect of this in producing glaciation would be slight. In the first place, being perhaps pushed farther north than during Pleistocene times, its area would decrease, for the distance around the earth in latitude 70° , for example, is much less than in latitude 55° . In the second place, even though the storms were numerous, there would be little precipitation. The winds drawn in from the south would come almost entirely from enormous deserts, where they could not possibly obtain moisture. Those drawn in from the north would come from regions of intense cold, where the oceans would be covered with ice, and the air could neither obtain nor hold much water. Thus, even though storminess were as great as in the Pleistocene ice age, there would be only scanty precipitation. Today in the northern parts of Canada and Siberia we have regions of intense cold which nevertheless show no trace of glaciation, although their mean temperature is perhaps as low as that of Greenland. In Pleistocene times glaciation did not extend to them, although the ice-sheets moved toward them from regions with more abundant precipitation. According to the cyclonic hypothesis, the conditions which prevail in these relatively small areas at present were magnified enormously during the Permian era, and thus the great "Red Northland" came into existence.

CONCLUSION

Further details of the relation of the cyclonic hypothesis to the climate of the geological past must be left for future investigation. In the ancient Permian times, according to the conditions of the hypothesis, our earth must have presented a curiously banded appearance, like Jupiter, with its cloudy bands and spots. On either side of the equator two bands of almost constant storm and cloud presumably encircled the entire globe, and perhaps almost merged with one another. Beyond them, in the middle latitudes of either hemisphere, a belt of aridity and of great deserts prevailed. There the air was always clear, and an observer on another planet would have been able to see large pinkish areas in the centers of widely extended transverse continents. Then in the far north and south there were probably two other belts where cloudiness prevailed, but where the clouds were not particularly dense. From age to age the banding has presumably changed, and it may be that in the various planets we can find some of the stages through which the earth has passed.

The picture of the Pleistocene and Permian glacial periods which has here been drawn is avowedly only a rough sketch, a first attempt at a task which will require the cooperation of scores of investigators. It must be regarded merely as an approximate statement of what would have happened in those times if events had occurred in accordance with the cyclonic form of the solar hypothesis of climatic changes. The most significant feature of the whole matter is, in a sense, its unexpectedness. A series of studies was carried on for the purpose of determining the cause of the changes of climate now in progress without special reference to the geological past. These studies led to the conclusion that the key to the solution of many climatic problems lies in Kullmer's law of the apparent relationship between the type of solar phenomena known as sun-spots and the type of terrestrial phenomena known as cyclonic storms. Taking the conclusions thus reached, we have simply magnified them. When slightly magnified, they seem to produce the results which have apparently occurred during the climatic changes of historical times. When more magnified, they seem to give the phenomena observed during the Pleistocene glacial epoch. When magnified very greatly, they seemingly lead to the highly specialized conditions of the great Permian epoch of glaciation. We have no direct evidence that any such change in either sun-spots or storms has taken place. We can merely say that if our conclusions as to the climate of the present are correct, and if the

present type of solar and terrestrial phenomena occurred formerly on a magnified scale, we should expect to find that the earth had experienced vicissitudes of climate like those which geology leads us to believe have actually occurred.

ORIGIN OF PILLOW LAVAS¹

BY J. VOLNEY LEWIS

(Presented before the Society December 30, 1913)

CONTENTS

	Page
General characters of pillow structure.....	592
Distribution of pillow lavas.....	595
In general.....	595
Germany.....	595
Saxony.....	595
Hanover.....	597
Bavaria.....	597
Hesse.....	597
France and Italy.....	599
British Isles.....	601
Wales.....	601
England.....	603
Scotland.....	606
Ireland.....	608
Sweden.....	609
Iceland and the Faroe Islands.....	610
East Indies.....	610
British America.....	611
Newfoundland.....	611
New Brunswick.....	611
Ontario.....	611
Hudson Bay.....	612
United States.....	613
Lake Superior region.....	613
Idaho.....	617
California.....	618
Alaska.....	619
Maine.....	620
Massachusetts.....	621
Connecticut.....	622
New Jersey.....	623
Chronological table of pillow lavas, pahoe-hoe and aa.....	629

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XLIII—BULL. GEOL. SOC. AM., VOL. 25, 1913

	Page
Pillow lavas and spheroidal structure in general.....	634
The confusion of hypotheses.....	637
Formation of pahoehoe lava.....	639
Formation of aa lava.....	641
Development of spheroidal and pillow-like forms.....	644
A theory of bulbous budding.....	646
General discussion.....	646
1. Highly liquid lava.....	646
2. Small continuous supply.....	646
3. Bulbous budding.....	647
4. Semi-molded, immobile forms.....	647
5. Separation of individual pillows.....	649
6. Interspheroidal cavities and breccia.....	649
7. Radial jointing.....	650
8. Degree of vesicularity.....	650
9. Hollow pillows.....	651
10. Extent of flow.....	651
11. Contact with water.....	652
12. Intrusive pillow lava.....	652
Acknowledgments.....	653

GENERAL CHARACTERS OF PILLOW STRUCTURE

The structure here called pillow lava has been variously described as cushion-like, sack-like, globular, spheroidal, ovoid, egg-shaped, ellipsoidal, lenticular, and concretionary. Once regarded as rare and peculiar, but now widely known in many countries, it has given rise to a great diversity of opinion among geologists concerning its real nature, and hence to an equal diversity of hypotheses as to the mode of its formation. Among the numerous causes to which it has been attributed are included: spheroidal weathering, spheroidal jointing, brecciation *in situ*, columnar jointing, with subsequent movement of the columns on each other, concretionary action, explosive eruption (bombs in agglomerate), normal flow of lava on land, viscous flow and fracturing of stiff lava, lava flow under water, intrusion into unconsolidated sediments, fracturing and partial remelting of lava crusts, and rapid cooling and parting into separate masses by the action of steam.

Sir Archibald Geikie² gives the following definition:

"Pillow-structure (Ellipsoidal structure)—an arrangement in many ancient and modern lavas where the rock before consolidating has separated into globular or pillow-shaped blocks from a few inches to several yards in diameter. The outer shell of these spheroids or ellipsoids is sometimes closer

² Textbook of Geology, London, 1903, vol. i, p. 136.

grained than the inside, and has rows of small vesicles running parallel to the outer surface. In the interstices between the blocks various sedimentary materials have sometimes been introduced, such as volcanic tuff, sandstone, shale, ironstone or chert."

The forms described are separate or nearly separate masses of lava that yield rounded or oval cross-sections in all directions, though in many localities they are molded in varying degree on one another or even flattened out like cushions or half-filled sacks, and in the latter case nearly or quite fill the space, without open interspaces (plates 15-21).³ These forms are to be clearly differentiated from the spheroidal jointing or ex-foliation due to weathering (see plate 25). Where spaces exist between the masses they tend toward a rude tetrahedral form, with concave sides (hence are roughly triangular in cross-section), and are generally filled in part with flakes and angular fragments of the same character as the curved surfaces of the bounding masses. Filling the remaining spaces in many localities and cementing the fragments into a breccia are a great variety of minerals that are commonly considered secondary. Prominent among these are chlorite, calcite, quartz, chalcedony, agate, and other cherty and flinty forms of silica, together with epidote and the wonderful series of the zeolites. In some regions but few of these minerals occur, while elsewhere, even in other parts of the same flow, they are developed in marvelous variety and abundance.

In some districts the interspaces are filled with radiolarian and other cherts, jaspers, and limestones or with shales and coarser terrigenous sediments. Some of these seem to have been gathered up from preexisting oozes or muds across or into which the lava flowed, and others appear to have fallen into the open spaces from subsequent deposits on the lava surface.

In many places the rounded masses are elongated and more or less flattened into a bale-like or bolster-like forms, and indeed some degree of elongation is a very general characteristic (plate 18, figure 1; plate 21, figure 1). In such cases there is commonly also a pronounced parallelism of the longest axes of the masses and a like, though less prominent, parallelism of the intermediate and shortest axes as well. Gradations into more irregular twisted and ropy lavas have also been observed, with half-formed pillows or ellipsoids attached to each other and to the solid massive lava of the flow by necks or along the sides, as in the typical Mesozoic

³ Hence Geikie's term, pillow lava, has been adopted here because it seemed, on the whole, more accurate and more appropriate for general application than such terms as spheroidal, globular, and ellipsoidal. Pillows, sacks, and cushions are subject to a wide range of form and the comparison suggests a truer conception of the structure than any of the other terms.

pillow greenstones of Alaska (plate 19) and in the modern lavas of Hawaii and Samoa (plates 22 and 23).

The individual pillows are very commonly sheathed in a film of glass from 2 or 3 to 25 or more millimeters in thickness (plate 16), and the microscope shows that this passes gradually into the crystalline lava of the interior. In many cases the rock is massive or only slightly vesicular, although some very light and spongy lavas are also known in this form. A vesicular or variolitic zone (or both) very commonly lies just within the glassy crust, and in some localities a flow-structure is developed parallel to the outer surface of each mass (plate 20, figure 1; plate 21, figures 1 and 2). Two or more concentric layers of alternating vesicular and solid lava are sometimes found, and the central portions of some pillows are extremely porous or even cavernous, the weathering out of such spongy interior leaving only hollow shells (plate 20, figure 2). Some nonvesicular spheroidal lavas also have in many of the masses a central or axial hollow resembling the pipe in a steel ingot (plates 16 and 17, figure 1).

The vesicular portions of pillow lava have been quite generally converted into amygdaloid, and cavities of all kinds are commonly more or less completely filled with the various minerals (calcite, zeolites, etcetera) previously referred to. In such cases the occurrence of empty spaces, either vesicular or interspheroidal cavities in the outcrops of the rock, is the result of the removal of these minerals by weathering.

A pronounced radial columnar jointing is very commonly developed in the pillows, and when these are broken down by the mechanical processes of weathering or the corrasive action of waves and streams they fall into tapering, pointed or wedge-shaped fragments (plates 15, 17, figure 1, and plate 19, figure 2). A concentric jointing or lamellar structure, so characteristic of spheroidal weathering, has been observed far less commonly (compare plate 21, figure 2, and plate 25).

In the metamorphic types of lava the characteristic structures are more or less masked by the results of subsequent processes. One of the most common, which is quite characteristic of the greenstones, is the development of chlorite from the glassy sheaths of the pillows and from the fragments in the interspaces, accompanied by the partial or complete chloritization of the ferromagnesian minerals throughout the mass of the rock (plate 17, figure 2). The chlorite in the interspaces generally has a schistlike structure parallel to the surfaces of the adjacent ellipsoids. This fact led some of the earlier observers to ascribe the pillow structure altogether to earth movements in which the lava had become involved, producing a gigantic brecciation and rubbing of the blocks on each other.

As already suggested, other early attempts to account for the structure include hypotheses of spheroidal jointing due to contraction while cooling, exfoliation due to weathering, and even concretionary processes. Among more recent investigators some have likened the rounded forms to the ropy flow structure of a viscous pahoehoe; others compare them to block lavas of the rugged aa type, assuming a certain degree of residual plasticity in the angular blocks. Subaerial flow, specified or implied, is a necessary condition in some hypotheses; but probably the majority of recent students of this phenomenon ascribe it to the influence of water on subaqueous eruptions or to the flow of lava into bodies of water or over water-bearing silts. Various combinations and modifications of these hypotheses have been advocated by different investigators, and some geologists hold that the evidence establishes the fact that pillow structure may be produced under a wide range of conditions.

Every known example of this structure occurs in basalt or some closely related variety of basic igneous rock. The greenstones in which it is so abundantly developed in the Lake Superior region and at many localities in Europe are no exception to this rule, since they are clearly recognized as chiefly basaltic rocks that have been modified in varying degree by hydration and mechanical processes. The peculiar basic rocks, with "albitized" feldspar and "chloritized" pyroxene, to which the name *spilite* has been given, are doubtless also modified basalts. In one or two examples the rock possessing this structure has been called a basic pyroxene andesite.

DISTRIBUTION OF PILLOW LAVAS

IN GENERAL

The wide range of pillow lavas, both geographically and geologically, their characteristics in different localities, and incidentally the persistent confusion of theory concerning the origin of the structure may best be indicated by a brief review of the descriptions of the better known occurrences in various countries. I have included here references to all literature on the subject that I have been able to find in a rather limited search of the larger scientific libraries of New York and Washington. The list is known to be incomplete, however, at least for Germany and the British Isles, and is probably so for other countries as well.

GERMANY

Saxony.—As early as 1834 C. F. Naumann⁴ described the conglomerate-like appearance of the greenstone schists of Hainichen, in the Kingdom

⁴ Erläuterungen zur geognostische Karte des Königreichs Sachsen, pt. 1, 1834, p. 69.

of Saxony. He observed fathom-large masses of the rock separated from one another by irregular fissures—some narrow, some wide—and these filled with minute fragments of the same rock. Such structures, he thought, could not well be exclusively the work of rushing torrents, and the supposed conglomerate was believed to have had its boulders ground together by earth movements in which it had been involved. In 1871 Naumann⁵ distinguished between the basal conglomerate of the Culm and a supposed greenstone breccia, but considered both to have been produced contemporaneously by brecciation *in situ*. Credner⁶ concurred in this conclusion.

Rothpletz⁷ recognized the "Grundconglomerat" of the Culm as a true conglomerate, but saw in its squeezed and faulted pebbles evidence of the force to which he attributed the origin of the supposed breccia in the accompanying greenstone. In other words, he concluded that the remarkable spheroidal structure of the greenstone was due to the action of intense orographic pressure on a rock that had previously been broken by a system of joints, so that movement took place throughout the mass, causing a rounding and partial brecciation by the grinding of the joint-blocks on one another. The rock is described as a dense, finely vesicular diabase, and the ellipsoidal masses attain maximum dimensions of 0.3 meter for the shorter and 1 meter for the longer axes.

Dathe⁸ observed that these dark-green amygdaloids are variolitic, and that the oval to egg-shaped masses of which they are composed are somewhat uneven on their surfaces and fit into each other. Hence he concluded that they were formed contemporaneously from the magma. He also found that the spheroids form layers that are approximately horizontal and occur throughout the whole thickness of the flow, being especially well developed at the bottom. Many of the broken masses showed a linear structure parallel to the outer surfaces, and in some of them the varioles are arranged in concentric layers. Dathe also called attention to the wide distribution of this structure in other parts of Vogtland, in the Upper Devonian of the Lobenstein-Saalburg region, and in the Fichtelgebirge.

The concentric arrangement of the amygdules parallel to the surfaces

⁵ Erläut. d. geogn. Karte der Umgegend von Hainichen im Königr. Sachsen, 1871, p. 11.

⁶ G. R. Credner: Das Grünschiefersystem von Hainichen im Königr. Sachsen. Zeitschr. für die gesammten Naturwiss., vol. xiii, 1876, pp. 117-245.

⁷ A. Rothpletz: Ueber mechanische Gesteinsumwandlungen bei Hainichen in Sachsen. Zeitschr. d. deutschen geol. Gesell., xxxi, 1879, pp. 355-398. "Die Breccienbildung des Aktinolithschiefers oder sogen. Grünschiefers von Hainichen." pp. 374-398. See also Erläut. zur geol. Specialkarte d. Königr. Sachsen, Sec. Frankenberg-Hainichen, 1881, p. 16.

⁸ E. Dathe: Beitrag zur Kenntniss der Diabas-Mandelsteine. Jahrb. d. Königl. Preuss. geol. Landesanstalt u. Bergakad. Berlin, 1883, pp. 410-448.

of the spheroids led Dalmer⁹ to the conclusion that the remarkable spheroidal structure that is so abundant about Neumark and Planitz must be original and not the result of weathering.

Hanover.—Nearly fifty years ago Credner¹⁰ described spheroidal and ellipsoidal structure in the mining district of Saint Andreasberg, in the Harz Mountains. The masses range from one-fourth of a foot to 2 feet in diameter and lie loosely on one another without filling the interstitial spaces. Each mass is coated with a vesicular crust one-fourth to one-half inch in thickness containing abundant chlorite.

Bavaria.—The altered aphanitic diabase of the Fichtelgebirge was described by Gregory¹¹ as "jointed" into spheroids from 80 millimeters to more than 1 meter in diameter. The masses are compact, but at a little distance from the surface and parallel to it is a band of variolite with varioles from 2 to 3 millimeters in diameter, decreasing in number and size on either side and passing into normal diabase. Some of the smallest masses are variolitic throughout. The origin of the spheroids is attributed to contraction during solidification, while still semiviscid on the exterior but fluid within. Presumably this is conceived as a subterranean process, for the author adds: "Under the pressure of the forces that drove them upward these rolled over one another and were drawn out into oval masses."

From the country north of the Fichtelgebirge Hoffmann¹² has described excellent examples of pillow structure in the dense greenstones at Wiedesgrüner Mühle, near Schauenstein. The masses are finely vesicular to slaggy, of rounded, elongated, or oval shape, and have their greatest diameters (6 to 8 feet) lying parallel. An elevation or depression in the surface of one is matched by a conformable irregularity in its neighbor, and from this it is concluded that they must have been formed contemporaneously from the fluid mass.

Hesse.—Ludwig¹³ has described spheroidal and ellipsoidal constituents of the Upper Devonian "Deckdiabas" as flow-surface phenomena:

"Man findet . . . im Schelder Walde und im Dilltale öfter Wechsel von in Schollen abgesonderten Massen, der Art mit kugelförmig abgesonderten

⁹ K. Dalmer: Erläut. zur geol. Specialkarte d. Königr. Sachsens, Sec. Planitz-Ebersbrun, 1885; Sec. Rösswein-Nossen, 1887. See also Sec. Plauen-Ölsnitz, 1887, by E. Weise.

¹⁰ H. Credner: Geognostische Beschreibung des Bergwerkdistriktes von St. Andreasberg. Zeitschr. d. deutschen geol. Gesell., vol. xvii, 1865, pp. 11-231.

¹¹ J. W. Gregory: The variolitic diabase of the Fichtelgebirge. Quar. Jour. Geol. Soc. London, vol. 47, 1891, pp. 45-62.

¹² F. Hoffmann: Uebersicht der orographischen und geognostischen Verhältnisse vom nordwestlichen Deutschland, vol. ii, p. 429.

¹³ R. Ludwig: Geol. Specialkarte des Grossherzogtums Hessen, Sec. Gladenbach, Darmstadt, 1870, pp. 34, 93, 96, 103, 106.

oder solchen, welche zusammengesetzt sind aus geflossenen Tropfen, Zapfen, Sphäroiden, gewundenen, abgerundeten Gestalten, wie man sie an den erkalteten Lavaströmen der nach tätigen Vulkane so oft sieht."

Denckmann and Streng¹⁴ observed at Herborn and Londorf similar phenomena, including rounded and elongated rolls and ropy forms, which they regarded as marking the cooling surfaces of lava, and Brauns¹⁵ has described analogous structures in the Upper Devonian diabases at Quotshausen and Homertshausen, in the Hessian hinterland. At the former an exposed surface showed rope-like and fluted lava, with rounded (wulst-artig) masses, the surfaces of which are coated with glass; at the latter locality the upper surface of one flow and the bottom of another that immediately overlies it are also glassy and characterized by thick, rounded, and sacklike masses. Heineck¹⁶ found "dickwulstige, runde Formen, die sich als Oberflächformen erweisen" in the diabase flows about Herborn.

Brauns¹⁷ calls attention to the wide-spread occurrence of well preserved "stream-surface" phenomena in the "Deckdiabas" of uppermost Devonian, which consist of rounded swells and large and small spheroids closely packed together and attached to the massive rock by short, thick necks. The crusts are glass, with a variolitic layer beneath it in some places, and the masses have a radial, spokelike jointing. The plates illustrating this article show typical pillow lava, both in surface features and in cross-sections.

Reuning¹⁸ found along the newly constructed road from Herborn to Dreidorf that the structures heretofore called "flow," "surface," and "cooling" forms, such as characterize the upper surfaces of many modern flows, in reality constitute the whole thickness of many of the flows, and that many of the rounded, spheroidal, ellipsoidal, and roll-like masses, which appear at first glance to be entirely isolated individuals, are connected to each other by short, little necks. The diameters range up to more than a meter; all are coated with glass, and radial, spokelike jointing is common. The filling between the masses is chiefly granular calcite in some beds, more chloritic in others, and at one place (near Neumühle) large spheroids are embedded in a light gray limestone that is rich in

¹⁴ A. Denckmann and A. Streng: *Zeitschr. d. deutschen geol. Gesell.*, vol. 39, 1887, pp. 624, 625.

¹⁵ R. Brauns: *Mineralien und Gesteine aus dem hessischen Hinterland. Zeitschr. d. deutschen geol. Gesell.*, vol. 41, 1889, pp. 491-544.

¹⁶ Fr. Heineck: *Die Diabase an der Bahnstrecke Hartenrod-Ueberthal bei Herborn. Neues Jahrb. Min., etc., B. B.*, vol. xvii, 1903, pp. 77-162.

¹⁷ R. Brauns: *Der Oberdevonische Deckdiabas, Diabasbomben, Schalstein, und Eisenerz. Neues Jahrb. Min., etc., B. B.*, vol. xxi, 1906, pp. 302-323.

¹⁸ Ernst Reuning: *Diabasgesteine an der Westerwaldbahn Herborn-Dreidorf. Neues Jahrb. Min., etc., B. B.*, vol. xxiv, 1907, pp. 390-459.



PILLOW BASALT

Showing radial columnar jointing and hollow spaces from which the interstitial material has been removed by weathering. The hammer is one foot long. The locality is McBride avenue, between Rockland and Howard streets, three-eighths of a mile above Passaic Falls, Paterson, New Jersey.

crinoid remains. In places among the pillows there are continuous masses of limestone with dimensions up to 30 by 60 centimeters.

Reuning ascribes the origin of the pillows to a violent submarine eruption. The lava, boiling up with great force and coming into immediate contact with the water, was rent asunder and became balled-up into the various spheroidal, ellipsoidal, and roll-like forms, which cooled quickly and settled down irregularly on one another. The larger limestone masses were thought to have been brought up from the depths with the eruption, or else the lava masses sank into a soft, limy ooze and inclosed it among themselves. Several of Reuning's plates show excellent examples of pillow structure, and one of them shows a large cross-section of a pillow with radial jointing.

FRANCE AND ITALY

Mazzuoli and Issel¹⁹ have described from the eastern coast of Liguria a dense basic rock with a kidney-shaped nodular structure, the masses being 10 to 15 centimeters in diameter and having variolitic surfaces and concentric internal structure consisting of bands of different color and hardness. These are arranged like the elements of a pudding in a paste for the most part epidotic. The masses are called concretionary ("arnione di concentrazione").

Cole and Gregory²⁰ described the porphyritic and variolitic diabase of Mont Genève, on the French-Italian border, as a rock "which weathers into great rounded spheroids, the faces of which appear to be surfaces of cooling, since the masses are often jointed within into radial prisms." These masses resemble pillows and soft cushions piled on and pressed against one another, so that each cliff shows a number of swelling surfaces and curving lines of junction. There are small vesicles in the rock, especially toward the surfaces of the masses, and in places the whole rock is vesicular and slaggy. A layer of variolite, from 1 to 7 or 8 centimeters thick, believed to be a devitrified tachylite, forms the outer crusts, the varioles of which are drawn out parallel to the surface and range from almost microscopic to 5 centimeters in diameter.

"It is possible that the surfaces of ordinary spheroids of contraction, even in the heart of a cooling mass, may differ appreciably from the more central portions and, consolidating more rapidly, exhibit a vitreous structure. . . . But we prefer to read in the irregular shape and involuted surfaces of the

¹⁹ L. Mazzuoli and A. Issel: *Relazione degli studi fatti per un rilievo delle masse ofiolitiche nelle riviera di Levante (Liguria)*. Boll. R. Comit. Geol. d'Italia, vol. xii, 1881, pp. 313-349.

²⁰ G. A. J. Cole and J. W. Gregory: *The variolitic rocks of Mont Genève*. Quar. Jour. Geol. Soc. London, vol. 46, 1890, pp. 295-332.

diabase masses of Mont Genève evidence of the rolling over of the lavas among themselves; and we are led to regard the presence of variolitic selvages throughout such great thicknesses of rock as largely due to movements taking place within a crater."

Comparison is made with the movements of lava in the crater of Kilauea, the Mont Genève rock being considered the equivalent of "only the lower layers of the volcanic caldron," the upper portions having been removed by erosion.

Rocks described as "variolitic tuffs" are associated with the diabase, but "they may, indeed, be friction-breccias or lavas broken up while viscid or volcanic tuffs." Spherical "bombs" are abundant, coated with variolite and contained in a matrix that is regarded as ash. The masses have a radial columnar structure, which gives a tessellated appearance on the surface. The largest measured 70 by 43 by 45 centimeters. Small fragments are often scoriaceous and very angular and the matrix contains many particles and fragments of basic glass. Compared with the rugged aa flows of Hawaii, these beds are found dissimilar. "Neither the arrangement of the masses nor the globelike bombs correspond with the features so clearly described and figured by Professor Dana," and the authors are led to consider these deposits as the products of true explosive action.

Zaccagna²¹ has described a spheroidal diabase, with variolitic crusts identical with that of Mont Genève from Monte Viso, in the western Alps south of Mont Genève. He considered the spheroidal forms, however, to be the result of weathering.

"Queste rocce verdi constano in massima parte di serpentina con qualche intercalazione di anfiboloscisto e di diabase. . . . Anche la diabase che trovasi nelle vicinanze inserita nel calcescisto è identica a quella eocenica ed ha come questa la particolarità di fornire colla decomposizione delle masse sferoidali. Non di rado nelle masse testacee della roccia in decomposizione trovasi una crosta variolitica identica a quella della massa del Mont Genève."

Platania²² has described the globular basalt at Acireale, on the eastern coast of Sicily, where two types of structure are found: (1) Large, with radial jointing, forming prismatic wedges, and (2) variable dimensions, with concentric cleavage, some of which inclose foreign rocks. Both are closely associated with tuff beds, and the globes are commonly slightly deformed, as if they had been pressed together while yet pasty. The crusts are glassy and the interspaces are occupied by clay and tuff. The spher-

²¹ D. Zaccagna: Sulla geologia delle Alpi occidentali. Boll. del R. Comit. Geol. d'Italia, vol. xviii, 1887, p. 387.

²² G. Platania: Geological notes of Acireale. The South Italian Volcanoes, ed. by H. J. Johnston-Lavis. Naples, 1891, pp. 37-44.

roids are compared to Johnston-Lavis's experiment of injecting a dense viscous liquid into another, which produced spherical forms, with narrow necks, that may be severed, leaving the globes detached; and the structure is thought to be "probably due to the injection of magma into a thick stratum of submarine silt, which occupies . . . the interspaces between the different globes."

BRITISH ISLES

Wales.—In 1881 Bonney²³ reported a "compact green rock with indubitable spheroidal structure . . . in places very distinctly spheroidal," in what had formerly been called a serpentine at Porthdinlleyn, Carnarvonshire.

Raisin²⁴ has described the spheroidal structure in the variolitic rocks of the Lley, Carnarvonshire, in which the masses are long and cushioned in appearance and some of them as much as 6 feet in diameter. Broken ones show a radial jointing toward the outer surfaces and a rhomboidal jointing within. Many of them contain "a zone of vesicles radially elongated as if gases had been prevented from escaping. Thus evidently a crust was formed at an early period, before the structures were completely solid." The outer portions consist of a chloritic and serpentinous aggregate which is thought to represent a glassy crust. The spheroids are regarded as contraction products and the glassy material as due to a secondary movement of lava which "partially thrust itself in between them," or possibly to differences in the glassy and cryptocrystalline character of the outer and inner portions of the spheroids, respectively, and to the different results of crushing on these portions. The structure at this locality has been more recently described as a pillow lava by Cox and Jones,²⁵ who call attention to the association of the rock with a peculiar "limestone" with beds and strings of jasper, which in places wrap round the pillows. The structure is extremely complicated and the rocks are probably of pre-Cambrian age.

The same authors describe from Sarn Melltelyn, near Pwllheli, in Carnarvonshire, a bed of pillow lava 10 to 12 feet thick overlain by about the same thickness of a rock of allied character which is not pillowy, and this is followed in turn by flinty mudstones and micaceous shales, prob-

²³ T. G. Bonney: On the serpentine and associated rocks of Anglesey, with a note on the so-called serpentine of Porthdinlleyn (Caernarvonshire). *Quar. Jour. Geol. Soc. London*, vol. 37, 1881, pp. 40-51.

²⁴ C. A. Raisin: Variolite of the Lley and associated volcanic rocks. *Quar. Jour. Geol. Soc. London*, vol. 49, 1893, pp. 145-165.

²⁵ A. H. Cox and O. T. Jones: On various occurrences of pillow lavas in North and South Wales. *Rept. Brit. Asso. Adv. Sci., Birmingham meeting, 1913*, p. 495; also *Geol. Mag.*, vol. x, 1913, pp. 516, 517.

ably of Lower Arenig age. A close jointed dark gray chert occurs between the pillows.

Pillow lavas from Anglesey were described by Blake²⁶ as rock that "weathers into some beautiful large spheroids, the interstices between which are filled with radiating zeolites." The glasslike substance outside of the spheroids was found to contain microlites of feldspar. The spheroidal structure was considered an original product of cooling and only emphasized by weathering, and the ordinary spheroidal weathering of basalt was thought to be the same. Cole²⁷ showed that the glassy coatings of the pillows at this locality are variolitic and bear the same relation to the diabase as the devitrified crusts at Mont Genève, running into crevices and wrapping round the masses. "This appearance is due to its having developed as a product of rapid cooling on the spheroidal surfaces of a lava." Silica has replaced much of the original rock, even the whole interior of some of the spheroids, leaving unchanged tachylitic crusts wrapping round masses of red jasper.

"This silica, which some would certainly associate with the action of hot springs, rising perhaps in pre-Cambrian times at the close of local volcanic activity, has actually replaced the igneous rock by a red or purple-red jasper."

The basic lavas of southeastern Anglesey have been described by Greenly²⁸ as

"composed of ellipsoidal or spheroidal masses piled and pressed upon one another as if they had been rolled over and over in a semiconsolidated condition. . . . Sometimes smaller ellipsoids or pillowy masses fit into gentle reentering curves in the sides of the larger ones, suggesting very vividly, hard though they now are, the rolling and pressing against each other of pasty yet individualized bodies. (Footnote: The structure is evidently distinct from ordinary spheroidal jointing produced after consolidation.)"

Varioles are arranged in zones near and approximately parallel to the surfaces, as in the Mont Genève rock. The associated red jasper is thought to be of radiolarian origin.

The remarkably cellular (amygdaloidal) rock that forms the peak and southern declivity of Cader Idris, Merionethshire, is thus described by Geikie:²⁹

²⁶ J. F. Blake: On the Monian system of rocks. *Quar. Jour. Geol. Soc. London*, vol. 44, 1888, pp. 463-547. The microscopic structure of the older rocks of Anglesey. *Rept. Brit. Asso. Adv. Sci.*, 58th meeting, 1888, pp. 367-420.

²⁷ G. A. J. Cole: The variolite of Ceryg Gwladys, Anglesey. *Sci. Proc. Roy. Dublin Soc.*, new ser., vol. vii, 1891-1892, pp. 112-120.

²⁸ Edward Greenly: The origin and associations of the jasper of southeastern Anglesey. *Quar. Jour. Geol. Soc. London*, vol. 58, 1902, pp. 425-440.

²⁹ A. Geikie: *Ancient Volcanoes of Great Britain*. London, 1897, p. 184.

"Its surface displays a mass of spheroidal or pillow-shaped blocks aggregated together, each having a tendency to divide internally into prisms which diverge [converge ?] from the outside towards the center."

This occurrence is also described by Cox and Jones,³⁰ who state that there is a little associated chert, and that the rock closely resembles that of Mullion Island, Cornwall.

At the extreme west of Pembrokeshire, Jeffreys Haven, on the north side of Saint Brides Bay, Thomas³¹ records the occurrence of a basic lava with good pillow structure in a series of quartzites and shales immediately beneath the Upper Llandovery shales. At Strumble Head, Pembrokeshire, occurs a variolitic rock which was formerly thought intrusive and which has been described as having "spheroidal jointing." Cox and Jones³² find here a succession of much altered highly basic flows, some of which have well developed pillow structure, while others show transitions to nonpillowy types. There is much associated chert, especially with those having a pronounced pillow structure. Typical pillows range from 1 foot to 18 inches in diameter.

England.—Fox³³ first described the pillow lavas of Mullion Island, south coast of Cornwall, as fine-grained greenstones

"of a peculiar globular or ellipsoidal structure, associated in certain parts of the island with bands, sheets, and lenticles of chert, shale, and limestone."

At the same time a more detailed description of the rocks and their structures was presented by Fox and Teall,³⁴ in which the greenstones are characterized as

"separated into rude rolls by curvilinear joints. The rolls show circular or elliptical outlines in cross-section and measure from a few inches to 2 feet in diameter. Flat surfaces of this rock, such as are exposed at many places at the base of the cliff, remind one somewhat of the appearance of a lava of the pahoehoe type."

The rolls tend to a parallel elongation. Bits of limestone are found between them and patches of chert and shale sticking to their surfaces. The stratified rocks are thin strips of cherts, shales, and limestones both underlain and overlain by igneous rocks and which can not be traced

³⁰ A. H. Cox and O. T. Jones. Loc. cit.

³¹ H. H. Thomas: The Skomer volcanic series (Pembrokeshire). Quar. Jour. Geol. Soc. London, vol. 67, 1911, pp. 175-214.

³² A. H. Cox and O. T. Jones. Loc. cit.

³³ Howard Fox: Mullion Island. Jour. Roy. Inst. Cornwall, vol. xii, 1893-1894-1895, pp. 34-38.

³⁴ Howard Fox and J. J. H. Teall: On a radiolarian chert from Mullion Island. Quar. Jour. Geol. Soc. London, vol. 49, 1893, pp. 211-220.

across the island. The chert is radiolarian and is interstratified with the shale in bands from one-fourth of an inch to several inches thick, as many as 30 bands of it occurring in a thickness of 3 feet. The ellipsoidal lava is regarded as having the character of an extrusive:

"The phenomena might be explained by the simple flow of a submarine lava, if such a lava possessed the power of insinuating itself between layers of deposit and tearing them up during its onward march."

Pillow lavas like those of Mullion Island were first recognized on the Cornish mainland at Gorran Haven in 1901,³⁵ and their occurrence at Tregidden, Porthallow, and intermediate points was demonstrated by Prior³⁶ in 1904. The rocks of the whole range, from Mullion Island to Porthallow, are described by Flett and Hill.³⁷ They occur in the Vryan series of the Ordovician, with accompanying intrusive and tuffs. They are much shattered in places along a zone of brecciation, but the original igneous structure is exceptionally well preserved. Fine-grained dark green rocks prevail, with small, rounded steam cavities, but highly vesicular varieties also occur. Epidotization has given rise to a bright green color, as in similar rocks of Anglesey, the Llyn, and other parts of Great Britain. Among the pillows are pale chert and shreds of laminated material "that suggest films of mud incorporated by the lava in its flow over the sea-bottom."

Ussher³⁸ found pillow basalts, with "inrolled interstitial sediment," including a little chert, in the Upper Devonian districts of Saltash and Devonport, Cornwall. At the Devonport workhouse quarry "detached pillows with concentric lines of steam cavities are found in the neighboring slates." Near Henn Point cherts terminate abruptly against the igneous rocks. To the naked eye these look like radiolarian cherts, but the microscopic characters do not confirm this impression.

The great sheet of pillow lava more than 200 feet thick, near Port Isaac, Cornwall, was fully described, in 1908, by Reid and Dewey.³⁹ As these authors indicate, the peculiar concentric structure had been noticed and figured by Whitley⁴⁰ as early as 1848, the lava appearing

³⁵ Mem. Geol. Survey of Great Britain. Summary of Progress for 1901, p. 17.

³⁶ G. T. Prior: Geol. Mag., 1904, pp. 447-449.

³⁷ J. S. Flett and J. B. Hill: The geology of the Lizard and Meneage. Mem. Geol. Survey of Great Britain. England and Wales. Expl. of sheet 359, 1912, pp. 31, 177-182, 183-185.

³⁸ W. A. E. Ussher: The geology of the country around Plymouth and Liskeard. Mem. Geol. Survey of Great Britain. England and Wales. Expl. of sheet 348, 1907, pp. 83, 94-97. See also Summary of Progress for 1904, p. 25.

³⁹ Clement Reid and Henry Dewey: The origin of the pillow lava near Port Isaac, in Cornwall. Quar. Jour. Geol. Soc. London, vol. 64, 1908, pp. 264-272.

⁴⁰ Nicholas Whitley: On the remains of ancient volcanoes on the north coast of Cornwall, etc. Thirtieth Ann. Rept. Roy. Inst. Cornwall, App. vi, 1848-1849, p. 62.

"as if it had rolled down a declivity and become partially cooled during its progress, and then consolidated into the rock which it now constitutes; in fact, much like the ends of bales of cloth piled one on another."

Reference was also made to this structure by Fox⁴¹ in 1902.

The flow consists of masses 2 to 8 feet in diameter, many of which have large central cavities ranging up to 2 feet. The pillows are highly vesicular (plate 20, figure 1), having only about one-half the density of the solid lava, and are associated with purely marine strata. Hence the authors believe the lava to be a submarine eruption consisting of separate spheroidal individuals that rolled on cushions of steam and so light that the whole sheet probably moved almost like a liquid.

"It seems therefore that the lava was in a true spheroidal state, each large drop ejected swelling up independently and forming a pillow more or less surrounded by escaping steam, so that the flowing mass on the sea bed formed a mobile sheet of rolling spheres, seldom touching one another till they cooled. As soon as the steam condensed, however, water would be sucked into the vesicles and the pillows would settle down."

The pillows are partially molded on each other and calcite fills the vesicles and interstitial spaces.

Geikie and Strahan⁴² have described a series of tuffs and basic flows (originally olivine basalts) interbedded with fossil-bearing Carboniferous limestones at Weston-super-Mare, Somerset. One sheet of dull green vesicular rock, 12 to 14 feet thick, shows marked ellipsoidal structure, with masses 2 to 8 feet in diameter, and a rugged scoriaceous upper surface, the irregularities of which are filled and overlain by fossiliferous limestone. Morgan and Reynolds⁴³ found the rock locally variolitic, and Boulton⁴⁴ concluded that the limestone between the pillows at Spring Cove, at any rate, came from the beds below. From a study of the associated limestones and their fossils, Strahan⁴⁵ concluded that the lavas were parts of a submarine volcanic eruption which merely interrupted the deposition of the fossiliferous limestone. Some of the more hardy species began to struggle back immediately afterward and their remains are

⁴¹ Howard Fox: Some coast sections in the parish of St. Minver. *Trans. Roy. Geol. Soc. Cornwall*, vol. xii, 1902, p. 670.

⁴² A. Geikie and A. Strahan: Volcanic group in the Carboniferous limestone of North Somerset. *Mem. Geol. Survey of Great Britain. Summary of Progress for 1898*, pp. 104-111. See also Geikie's *Textbook of Geology*, 4th ed., 1903, vol. ii, p. 757.

⁴³ C. L. Morgan and S. H. Reynolds: The igneous rocks associated with the Carboniferous limestone of the Bristol district. *Quar. Jour. Geol. Soc. London*, vol. 60, 1904, pp. 137-157.

⁴⁴ W. S. Boulton: On the igneous rocks at Spring Cove, near Weston-super-Mare. *Quar. Jour. Geol. Soc. London*, vol. 60, 1904, pp. 158-169.

⁴⁵ A. Strahan: *Geogr. Jour.*, vol. xxxix, 1912, p. 130.

found with alternating coarse and fine tuff beds above. When the waters finally cleared, a teeming fauna again overspread the spot.

Scotland.—South of Tayvallich, in Argyll, Peach⁴⁶ found sheets of slaggy andesitic basalt, with marked pillow structure (plate 21, figures 1 and 2); intercalated with the black schist and limestone of the Dalradian series (pre-Cambrian). There are also accompanying beds of tuffs and agglomerates. According to Dewey and Flett,⁴⁷ these rocks continue through Argyll past Loch Awe and representatives are again met with at Ardwell, in Banffshire. Pillow structure in the Lower Carboniferous lavas near Millstone Point, Argyll, northeast of the coast of Arran, is clearly shown in a photograph that I have obtained from the Geological Survey of Great Britain.

In Bute pillow structure occurs in the basic lavas of the Cement Group (Lower Carboniferous) at Corrie, in the Island of Arran; also in similar lavas of supposed Arenig age at Torr na lair Brice, north side of North Glen Lannox, Arran, as shown by the Survey photographs.

Pillow lavas in the Silurian rocks of the south of Scotland, particularly well shown along the coast near Ballantrae, in Ayrshire (plate 20, figure 2), have been described by Peach, Horne, and Teall.⁴⁸ The rocks include a series of much altered basic and intermediate lavas and tuffs, the micro-litic, nonporphyritic members of which show well developed pillow structure in many places. Amygdules are arranged in concentric layers and are generally more abundant toward the outside of the masses. The pillows range from a few inches to several feet in diameter and lie with their longest axes parallel to the stratification of the sedimentaries. The spaces between are filled in various places with calcareous matter, flinty shale, chert, and jasper, the calcareous materials being confined mainly to the surfaces of the flows.

Geikie⁴⁹ has described the pillow lavas in the Carboniferous rocks of Fife, which are basic basalts of the "picrite type," many of them thoroughly vesicular from top to bottom and full of dirty green amygdules. These are much decomposed, but others are fresh compact blue or black basalts and in some places columnar. Some of the flows are partly one and partly the other, the fresh parts being generally surrounded by the decayed amygdaloid.

⁴⁶ B. N. Peach: Mem. Geol. Survey of Great Britain. Scotland. Summary of Progress for 1903, p. 69.

⁴⁷ Geol. Mag., vol. viii, 1911, p. 241.

⁴⁸ B. N. Peach, John Horne, and J. J. H. Teall: The Silurian rocks of Britain. Mem. Geol. Survey of Great Britain, vol. i, Scotland, 1899, pp. 84-86, 367, 431, and pls. i, ii, iv, v, vi.

⁴⁹ A. Geikie: The geology of central and western Fife and Kinross. Mem. Geol. Survey of Great Britain. Scotland, 1900, pp. 54, 55, 62, 64, 69, 72, 74.

**PILLOW BASALT**

Showing interstitial tachyite (glass) breccia with zeolites, etcetera, separating the rounded masses. The large spheroid to the left of the center also shows a small pipe-like cavity. The hammer is one foot long. The locality is the quarry of the Paterson Crushed Stone Company, at West Paterson, New Jersey.



FIGURE 1.—PILLOW BASALT

Showing radial jointing (in the two upper masses), flattened pipe-like vacuoles (in the lower ellipsoid), and interstitial tachylite breccia, cemented by zeolites, etcetera. Secondary minerals are also developed in the pipe-like cavities. The hammer is one foot long. The locality is the quarry of Francisco Bros., at Great Notch, New Jersey.



FIGURE 2.—GLACIATED SURFACE OF ELY GREENSTONES, SHOWING "ELLIPSOIDAL PARTING"

The locality is one mile east of Soudan, Vermilion iron-bearing district, Minnesota. Photograph by the U. S. Geological Survey. Monograph xlv, plate iv-A

PILLOW BASALT AND GLACIATED SURFACE OF ELY GREENSTONE

"A remarkable feature of many of them is their subdivision into large, irregular, sack-like or pillow-shaped blocks, which may have their central portions more largely vesicular than the rest. These ellipsoids were formed during the flow of the still moving lava along the floor of the lagoon or sea. The interstices between them have often been filled in with fine tuff, which was stratified horizontally from side to side in the fissures before the lava was covered by the next outflow of molten material. In some cases portions of the still fluid lava in the heart of the mass were forced into the interstices and now appear as veins of finely cellular basalt. The lava sheets range from 8 or 10 to 40 feet or more in thickness" (pages 54, 55).

"This well-marked 'pillow structure' appears to indicate that, while still moving as molten masses, they separated into irregular ovoid, sack-like or pillow-shaped blocks of all sizes, from less than a foot to 5 or 6 feet in length. These blocks are frequently most cellular in the center, the vesicles being there largest in size and most crowded together. In other cases the vesicles are grouped around the margin and sometimes more particularly along one side of each ellipsoid. In the interstices between the blocks fine tuff and ashy sandstone may sometimes be seen, showing that the rude boulder-like masses were more or less separated from each other, so as to allow fine sediment to be dropped into the interspaces. This sediment is stratified horizontally or in the same direction as the general bedding-plane of the lava in which it lies.

"As they rolled along over the lagoons and pools of the time the basalts now exposed on the shore west of Pettycur caught up and involved large quantities of the muddy and calcareous sediments which lay in their way" (page 62).

In the southern borders of the Highlands, says Geikie,⁵⁰ apparently a strip of Arenig rocks has been wedged in against the Highland schists along the great boundary fault with radiolarian cherts like those of the south of Scotland and in the same sequence. The dull green diabasic lavas show conspicuous pillow and sack-like forms in the ravines of Forfarshire, and the igneous rocks are underlain with cherts as in Ayrshire. These rocks are about 50 miles from the nearest corresponding formations of the southern uplands, with which they may have been continuous, as possibly also with the north of Ireland, where this series, probably Arenig, attains its greatest development.

From a review of the British examples, in 1911, Dewey and Flett⁵¹ concluded that "the pillow lavas are a group of basic igneous rocks that occur, in our experience, only as submarine flows." The frequent association of cherts, many of them radiolarian, with this structure in Great Britain, even where the flows are in coarse, shallow-water sediments, sug-

⁵⁰ A. Geikie: *Ancient Volcanoes of Great Britain*. London, 1897, p. 201.

⁵¹ H. Dewey and J. S. Flett: On some British pillow lavas and the rocks associated with them. *Geol. Mag.*, vol. viii, 1911, pp. 202-209, 241-248.

gests a genetic connection. Magmatic vapors or solutions rich in dissolved silicates of soda and other bases would be exhaled from the rocks as they cooled and some would escape into the sea. It is thought that these siliceous waters may have furnished favorable conditions for the increase of radiolarians, diatoms, and other silica-secreting organisms. The direct deposition of the silica among the pillows does not seem to have been considered by these authors, although many of the British and other examples have jaspers and nonradiolarian cherts between the masses, and in some cases the rock itself has been extensively replaced by silica, as shown by Cole.⁵²

Ireland.—In the Lough Mask region of western Connaught the pillows are compressed into rudely polygonal forms, says Geikie,⁵³ and the vesicles are greatly drawn out in the direction of the tension (at Bohaun, 9 miles south of Westport). By more shearing the pillows disappear and their crusts are broken up as fragments in a matrix of green schist. The lavas are andesites and more basic rocks of Bala (Ordovician) age. Some are strongly vesicular and sack-like structure is conspicuous in places.

An immense development of pillow lavas is described by Gardiner and Reynolds⁵⁴ as the most marked feature of a great series of igneous rocks of the Kilbride Peninsula, County Mayo. The rocks are "spilites" associated and interbedded with cherts, grits, breccias, flow-breccias, and shales of Arenig (Ordovician) age. They are dark green to purplish rocks, somewhat vesicular, some of them markedly so, and the pillows are generally more vesicular around the borders than in the center, or consist of concentric layers of vesicular and solid lava. Irregular strings and patches of chert fill spaces between the masses and form a network around many of them. Rarely a large mass of chert is found in the center of a spheroid. These cherts are believed to have been formed subsequently to the consolidation of the rock and chiefly through infiltration. An illustration of the Kilbride pillow structure accompanying this paper is remarkably like that of West Paterson and Great Notch, New Jersey (compare plates 15-17).

On the east coast of Ireland (Dungarvan Harbor and northeastward) crushed cherts, igneous rocks, sandstones, etcetera, occur between the Paleozoic on the south and the schists on the north, in the same relations as along the border of the Scotch Highlands, but in a much broader area and with better opportunity to observe the relations. Besides intrusives,

⁵² G. A. J. Cole: Proc. Roy. Dublin Soc., new ser., vol. vii, 1891-1892, pp. 112-120.

⁵³ A. Geikie: Ancient Volcanoes of Great Britain. London, 1897, p. 252.

⁵⁴ C. I. Gardiner and S. H. Reynolds: The Ordovician and Silurian rocks of the Kilbride Peninsula (Mayo). Quar. Jour. Geol. Soc. London, vol. 68, 1912, pp. 75-102.

tuffs, and agglomerates, there are dull greenish fine-grained diabases, chiefly porphyritic, and some quite slaggy.

"One of the most conspicuous features in some of these lavas is the occurrence of the same sack-like or pillow-shaped structure which has been already referred to as so marked among the Arenig lavas of Scotland. . . . occasionally interleaved with gray flinty mudstones, cherts, and red jaspers, which are more particularly developed immediately above."⁵⁵

Amygdaloidal diabases with pillow structure occur with fragmental volcanics and intrusive igneous rocks for 12 miles near Slane and others south of Drogheda, associated with radiolarian cherts of Lower Llandeilo (Ordovician) age.

SWEDEN

Sundius⁵⁶ has described fully the pillowy structures that characterize the basal greenstone of the Kiruna (pre-Cambrian ?) series of regionally metamorphic volcanics and sedimentary rocks. The rounded massive portions of the rock range from a few decimeters to more than half a meter in diameter and are separated by dark hornblende "schlieren," with whitish streaks of scapolite, the whole resembling an agglomerate. It is not sedimentary, however, but formed, according to the author, "by the crowding of viscous lava bodies (pillows)." Common features are radial jointing and a concentric structure consisting of a glassy outside crust, bands of vesicles, and sometimes of variolites and differently colored layers. The longest axes are parallel to the "surfaces of deposition," and in some places there is a concentration of vesicles on the upper side of the pillows.

The characteristic skeleton crystals, microlites, and dark pigment of the original glassy coatings of the pillows are well preserved, although largely replaced by scapolite, which has also been extensively developed by regional metamorphism in other rocks of the district of very different composition. There is also much schistosity developed in places. Hornblende amygdules occupy vesicles elongated at right angles to the surfaces of the pillows.

"As a conclusion from evidence found in the field and under the microscope it appears that the occurrence of the pillows must be considered a flow-phenomenon in the lavas, where each pillow has formed an individual with its own surface of cooling. At Pahtosvaara the pillows occur everywhere in the fine grained varieties of the soda-greenstones, and when I have been able to distinguish separate lava flows they appear along one of the surfaces or, in one case, throughout the whole thickness of the bed."

⁵⁵ A. Geikie: *Ancient Volcanoes of Great Britain*. London, 1897, pp. 239-244.

⁵⁶ N. Sundius: Pillow lava from the Kiruna District. *Geol. Fören. i Stockholm Förel.*, vol. 34, 1912, pp. 317-333.

Comparing with similar structures that have been interpreted as submarine flows in Great Britain and elsewhere and considering the overlying Kurravaara conglomerate, "whose rounded and water-worn pebbles show it to be a marine deposit," the author concludes that contact with water has been the factor that favored the development of the pillows.

ICELAND AND THE FAROE ISLANDS

Johnston-Lavis⁵⁷ mentions having seen many beautiful examples of pillow lavas in Iceland in which the lavas had the appearance of having entered soft sediment on the sea-floor. Parts of Cape Reykjanes, at the southwestern extremity of the island, furnish good examples. Anderson⁵⁸ refers to the lava stream that crossed Lake Myvatn, in northeastern Iceland, and extended some miles down the valley below the lake. A number of spiracles were formed by the water and the mud; the larger ones built cinder cones and the smaller ones, chiefly on the lava stream below the lake, where the action was less violent, formed small cones made up of lava masses comparable in size and shape to pillow lava.

In 1880 James Geikie⁵⁹ attributed to weathering the numerous examples of spheroidal structure that he observed in the Faroe Islands. Whereas in ordinary flow structure the amygdulites show a distribution in parallel horizontal lines, "they also occasionally show a kind of curled, coiled, or involved arrangement, as if the rock had been rolled over on itself while in a plastic or viscous state." Archibald Geikie⁶⁰ also speaks of the tendency of the vesicular basalts of the east side of Sudero to weather into globular forms resembling agglomerates. It seems highly probable that some of these will prove on reexamination to be true pillow or ellipsoidal basalts.

EAST INDIES

Verbeek⁶¹ has described a series of melaphyres of "spilitic type" in the Island of Ambon, Dutch East Indies. A bed with amygdulites of calcite and chalcedony is composed of irregular spheroids from the size of a man's head to a meter in diameter. The masses are broken by radial, calcite-filled joints and coated with a black lustrous resinous tachylite. This glass and its alteration products also fill the spaces between the spheroids. The altered dull gray rock within consists of basic plagioclase in a brown

⁵⁷ H. J. Johnston-Lavis: *The South Italian Volcanoes*. Naples, 1891, p. 43 (foot-note).

⁵⁸ T. Anderson: *Quar. Jour. Geol. Soc. London*, vol. 64, 1908, p. 271.

⁵⁹ James Geikie: *On the geology of the Faroe Islands*. *Trans. Roy. Soc. Edinburgh*, vol. xxx, 1883, pp. 217-269.

⁶⁰ Archibald Geikie: *Ancient Volcanoes of Great Britain*. London, 1897, pp. 258, 259.

⁶¹ R. D. M. Verbeek: *Description géologique de l'île d'Ambon*. *Jaarboek van het Mijnwezen in Nederl. Oost-Ind.*, Batavia, vol. xxxiv, 1905.

glass basis, with pseudomorphs after augite and olivine. The glass coating contains fresh olivine and feldspar, but augite is lacking.

BRITISH AMERICA

Newfoundland.—Daly⁶² has described the variolitic pillow basalts of extreme northern Newfoundland, where they constitute flows 60 meters thick made up of round, smooth, bale-like and pillow-like ellipsoidal masses which are discontinuous and, as a rule, perfectly individualized. The whole rests on solid basalt about 1 meter thick. The masses range in size from 5 centimeters to 2 meters or more in maximum diameter, and the interstices between are filled with coarsely crystallized calcite, quartz, and dark cherty masses. Numerous radial cracks in the pillows are filled chiefly with calcite and a little quartz. These cracks are commonly widest and most numerous at the center, recalling the gaping cracks of many septaria, and are attributed to contraction while cooling. The rock is highly vesicular, the masses are slightly indented at their points of contact with each other, and the larger ones are flattened parallel to the dip of the accompanying strata. "In some cases the surfaces of single pillows, weathered out from their calcite matrix, were seen to have the exact appearance of ropy lava." The varioles tend to a concentric arrangement and increase in both size and abundance toward the center of the masses.

Daly finds the "detailed surface of pillow lavas more like that preserved by pahoehoe than like the ragged surface of aa blocks," and he concludes that their origin is due to "extrusion of basic lava into seawater of some depth."

New Brunswick.—Ells⁶³ described doleritic rocks from northern New Brunswick with a "concretionary structure," the "concretions" varying in size from 6 inches to several feet in diameter, and on broken surfaces disclosing a circle of small holes in dots around the outer margin.

Ontario.—In the greenstones of the Lake of the Woods region Lawson⁶⁴ found a structure, "apparently concretionary" and closely resembling in appearance the associated lenticular agglomerates, and the rock of which is similar to the greenstone schist that constitutes the paste of the agglomerates.

"This structure consists in the rock being divided into more or less irregular spherical or ovoid masses varying in diameter from 2 or 3 inches to as many

⁶² R. A. Daly: Variolitic pillow lava from Newfoundland. *Am. Geol.*, vol. xxxii, 1903, pp. 65-78.

⁶³ R. W. Ells: Report on the geology of northern New Brunswick. *Geol. and Nat. Hist. Survey of Canada*, 1881, p. 24D.

⁶⁴ A. C. Lawson: Report on the geology of the Lake of the Woods region. *Geol. and Nat. Hist. Survey of Canada*, 1885, pp. 51-53CC.

feet. The ovoid masses are not in close contact but are separated from one another by an interstitial material. The concretionary masses are, at their points of nearest approximation to one another, generally about a half an inch or an inch apart, no matter what may be their size, so that when the ovoid masses are large the interstitial material appears in sections as thin anastomosing sheets in which is developed a schistosity parallel to the outlines of the ovoid masses they enclose. The interstitial filling is generally of a darker color, more chloritic, softer, and a finer, more homogeneous texture than the ovoid masses and weathers out often leaving the latter, in the sections afforded by glaciated surfaces, surrounded by sharp little trenches. . . .

"The ovoid masses are uniformly arranged as regards the direction of their long axes, and each one is surrounded by a sharp border, half an inch wide, of a dark greenish-gray color, which has been more resistant to weathering agencies than the rest of the rock."

In portions of the greenstone that have been metamorphosed into hornblende schist the interstitial matter forms thin anastomosing sheets of dark-green soft chloritic material, some of which lose themselves in tapering disconnected fashion in the main mass of the rock.

Willmott⁶⁵ found the greenstone schists of the Michipicoten area characterized in many places by the same "elliptical" structure or "ellipsoidal parting," as described by Clements in the Hemlock formation of the Crystal Falls district and in the greenstones of the Vermilion district. They are regarded as undoubted lava flows, but the origin of the structure is not discussed.

Exactly similar greenstones have been described by Allen⁶⁶ from the Woman River district, in the Sudbury Mining Division of Ontario. These and similar greenstones of the Lake Superior region in general are thought to be of subaqueous origin.

Hudson Bay.—In an "Algonkian basin" along the southeast shore of Hudson Bay, where the formations resemble in many respects those of the Lake Superior region, Leith⁶⁷ interpreted the "ellipsoidal or pillow parting" in basalts of the Richmond group as evidence of subaqueous eruption.

"These were poured out approximately along the shores and tidal flats, for the coarse sediments immediately below and above them exhibit the wide variety of ripple and current marks duplicated in the tide flats of the shore today. Also the flows themselves show not only basaltic, amygdaloidal, and scoriaceous textures resulting from surface cooling, but the peculiar ellipsoidal

⁶⁵ A. B. Willmott: The Michipicoten Huronian area. *Am. Geol.*, vol. xxviii, 1901, pp. 14-19; also The nomenclature of the Lake Superior formations. *Jour. Geol.*, vol. x, 1902, pp. 67-76.

⁶⁶ R. C. Allen: Iron formation of Woman River area. Eighteenth Rept. Ontario Bureau of Mines, 1909, pt. i, pp. 254-262.

⁶⁷ C. K. Leith: An Algonkian Basin in Hudson Bay: A comparison with the Lake Superior Basin. *Econ. Geol.*, vol. v, 1910, pp. 227-246.

or pillow parting, often ascribed to subaqueous cooling, indicating substantially shore or shallow water conditions."

These are overlain unconformably by a series of limestones, sandstones, and quartzites of the Nastapoka group.

"Then came the great outburst of vulcanism . . . surface basalts, giving evidence by the thinly bedded, ripple-marked sediments above and below and between them, and by their own combination of ellipsoidal with basaltic, amygdaloidal, and scoriaceous textures, of extrusion at or near water level, not improbably along tidal flats. . . .

"The basalts are all characterized by an abundance of jasper veins, jasper filling the amygdules, jasper cement between the blocks of ellipsoidally parted flows. Striking indeed is the brightly colored jasper cement outlining the pillow forms on many of the beautifully exposed glaciated surfaces."

UNITED STATES

Lake Superior region.—Williams⁶⁸ found some of the greenstone schists of the Menominee and Marquette districts characterized by division into oval or lenticular areas which interlace and are separated by finely schistose material of much finer grain, at first glance resembling the spheroidal weathering of many eruptive rocks. The spheroidal, ovoid, lenticular, and more irregularly shaped masses, differing much in size and form, often exhibit a tendency to fit together like stones in a mosaic, but everywhere separated by interlacing bands of softer, more schistose, and generally darker material, which winds about the massive cores, becoming thinner and thicker as the masses approach each other or are more widely separated by the rounding of corners (compare plate 17, figure 2). This is not an agglomerate or a concretionary structure. Possibly in some cases it may be due to contraction which has produced spheroidal parting, the author suggests, like perlitic structure on a large scale; but on the whole he regards Rothpletz's explanation of similar structures in central Saxony as the true one—that is, the rock masses, already finely subdivided by joint cracks, have had the corners of the individual blocks rounded and the interstitial matter produced by the rubbing of the blocks together under intense orographic pressure.

Winchell⁶⁹ described similar ellipsoidal greenstones from Ely, Minnesota (plate 17, figure 2), as agglomerates, which he believed were produced by the falling of volcanic bombs into the sea. He observed that about the peripheries of the masses there are numerous radial tubes,

⁶⁸ G. H. Williams: The Greenstone schist areas of the Menominee and Marquette regions of Michigan. Bull. U. S. Geol. Survey, No. 62, 1890, pp. 137, 166-168, 203, 204.

⁶⁹ N. H. Winchell: The Kawishiwin agglomerate at Ely, Minn. Am. Geol., vol. ix, 1892, pp. 359-368.

about an inch apart, having a diameter of about 2 millimeters and a maximum length of about 1 inch. These are normally filled with calcite.

Winchell⁷⁰ took exception to the dynamo-metamorphic origin of the Lake Superior greenstones advocated by Williams. While there had been some later pressure and stretching, he questioned the competency of pressure to produce both the parallel banding of the schists and the schistose layers that wind round and separate the spheroidal masses. In a later publication,⁷¹ after describing other occurrences of greenstones, which consist of rounded masses, with the "curiously amygdaloidal periphery" of radial pipe-like tubes filled with calcite or chalcedonic silica, the author again reiterates his conviction that they are largely of pyroclastic origin, but finally concedes that "their nature and origin are problematical."

Smyth,⁷² from a study of the Marquette greenstones, concurs in the opinion of Rothpletz and Williams that the spheroidal structure is of mechanical origin.

Clements⁷³ has described fully the ellipsoidal structure in the metabasalts of the Hemlock formation in the Crystal Falls district. Many of them resemble a conglomerate of rounded boulders, all of the same kind of rock, in a matrix of very small amount and very different color. These are associated with and grade into nonellipsoidal varieties, apparently constituting the surfaces of the flows, and in some cases the whole flow. The masses range from a few inches to 6 or 8 feet in diameter, with sections generally ellipsoidal in all directions, and the longest axes approximately parallel. Some of the ellipsoids "are only half formed—that is, attached by one side to the main unbroken part of the lava flow, the other side showing a rounded outline."

The amygdaloidal varieties are generally most amygdaloidal at the surfaces of the masses, and some of these are much more so at the top surface. Roughly radial jointing is visible in some of the masses. Some also show a transition into the chloritic matrix, which the author believes is clearly derived from the body of the rock and was probably originally a glass. Many interspheroidal spaces with triangular cross-section are filled with vein quartz instead of schistose material.

Clements points to the concentric arrangement of the amygdules as

⁷⁰ N. H. Winchell: The origin of the Archean greenstones. *Geol. and Nat. Hist. Survey of Minn.*, 23d Ann. Rept., 1895, pp. 4-35.

⁷¹ N. H. Winchell: The geology of the north part of St. Louis County. *Geol. and Nat. Hist. Survey of Minn.*, Final Rept., vol. iv, 1899, pp. 255-257.

⁷² H. L. Smyth: The Marquette iron-bearing district of Michigan. *Monograph U. S. Geol. Survey*, vol. xxviii, 1897, p. 155.

⁷³ J. Morgan Clements: The Crystal Falls iron-bearing district of Michigan. *Monograph U. S. Geol. Survey*, vol. xxxvi, 1899, pp. 112-124.

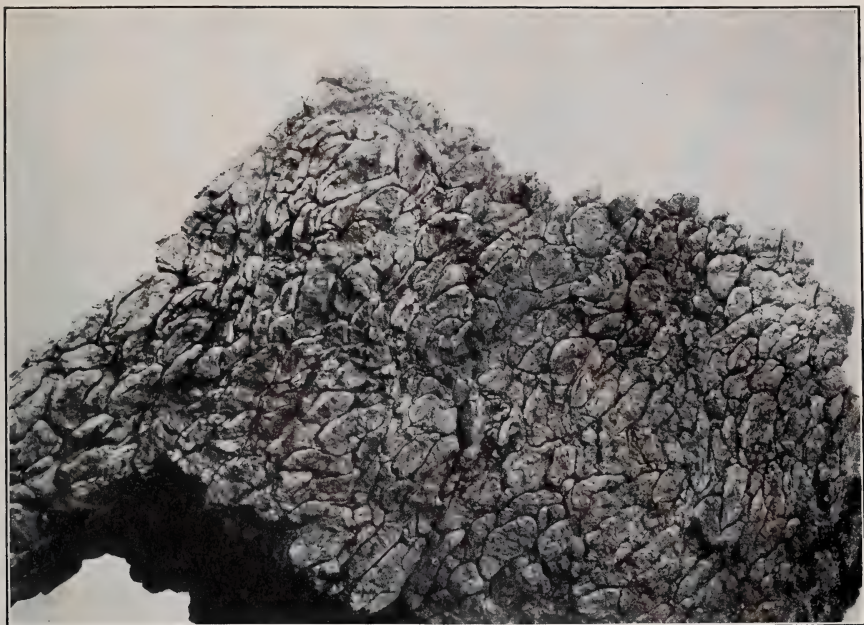


FIGURE 1.—PILLOW LAVA AT POINT BONITA, MARIN COUNTY, CALIFORNIA

The masses of lava up to 3 feet, rarely 5 feet, in diameter. Photograph by Prof. A. C. Lawson, loaned by Dr. F. L. Ransome



FIGURE 2.—“ELLIPSOIDAL STRUCTURE IN INTRUSIVE BASALT” (LAWSON)

The locality is Hunter Point, San Francisco Bay, California. Photograph from the U. S. Geological Survey. San Francisco Folio, plate v

PILLOW LAVA AND “ELLIPSOIDAL STRUCTURE IN INTRUSIVE BASALT”

proving the individuality of the masses before solidification, as shown by Dathe and Dalmer, and hence they can not be due to weathering. He compares them with the block lavas of Santorin and the aa lavas of Hawaii and attributes the structure to a

“slow forward movement and contemporaneous breaking up of the viscous lava. . . . This is the shape which viscous material would naturally tend to take when subjected to the rolling action attendant upon the onward motion of the stream of which they form an outer portion, or in certain cases the entire thickness.”

The rounding of the masses is thought to have been caused chiefly by rolling, but contraction due to cooling was regarded as a contributory cause, and later compression has broken off the jagged portions and partly filled the interstices.

Pillow structure is found almost universally in the Ely greenstones of the Vermilion district of Minnesota (plate 17, figure 2), with essentially the same characteristics as in the Crystal Falls district. Clements,⁷⁴ who describes the features of this structure in great detail, calls attention to the fact that in some places the amygdules are concentrated chiefly on one side of the pillows (the upper side), and that perfect transitions are found between the ellipsoidal and the nonellipsoidal basalt, both of essentially the same grain. The author considers these rocks to have had the same history as the similar ones at Crystal Falls, and hence that the shape of the ellipsoids was determined to a great extent by the rolling over and over of the blocks of aa lava, while still retaining some plasticity. At the same time they were contracting through cooling, and possibly subsequent pressure may have molded them to a certain extent.

Where they have been subjected to great pressure the ellipsoids have been mashed into disk-shaped bodies, and in extreme cases have been drawn out into bands, the material of the ellipsoids alternating with the thinner bands from the matrix.

Clements calls attention to the wide range of this structure, both geographically and geologically, in the various districts of the Lake Superior region.

“Thus, for example, it has been described from the Marquette and Crystal Falls districts of Michigan, and one can state with a fair degree of assurance from the occurrence of large quantities of greenstones in the Penoque-Gogebic of Michigan and Wisconsin that it also occurs there, although it has not been described from that district. It has also been observed by the writer in a number of places in the Menominee district of Michigan and in the Mesabi

⁷⁴ J. Morgan Clements: The Vermilion iron-bearing district of Minnesota. Monograph U. S. Geol. Survey, vol. xlv, 1903, pp. 144-152.

district of Minnesota. Lawson describes it in the rocks of the Lake of the Woods region. The same structure has been described from the Michipicoten iron-bearing district on the east side of Lake Superior by A. B. Willmott, and Dr. S. Weidman, of the Wisconsin Geological and Natural History Survey, states that it occurs in greenstones of supposed Huronian age in the vicinity of Wausau, Wis. It has been observed in the Archean greenstones of Lake Nipigon, in Ontario, Canada. As a result of field studies in the Keweenawan volcanics of the north shore of Lake Superior in 1900, the writer knows that it occurs also in them. . . . The rocks in which it occurs range from the Archean of the Vermilion district of Minnesota and the adjacent Canadian districts and the Marquette district of Michigan to the Keweenawan. It occurs within the greatest superficial area of the Archean."

According to Leith,⁷⁵ the structure of the basalts and metabasalts of the Mesabi district is identical with that of the various other districts to which reference has already been made.

"The ellipsoids themselves consist of basalt and vary in diameter from a few inches to one or two feet. They are separated by narrow bands of somewhat lighter or darker basalt. The ellipsoidal structure is one supposed to have been induced in the rock when it first cooled from an extensive magma, perhaps subaqueous."

Van Hise and Leith,⁷⁶ in summing up and revising the geology of the Lake Superior region, describe again the characteristic ellipsoidal structure of many of the greenstones, which exhibit every gradation from typical pillow lavas to schists that show a banding, owing to the difference in color between the deformed ellipsoids and their matrix. All of the iron-bearing formations, believed to be aqueous sediments, are "associated with basalts having conspicuous ellipsoidal structure which can be best explained as developed by flowing out under water." These are strongly contrasted in this respect with the basic lavas of the Keweenawan series.

After reviewing some of the studies that have led to diverse views on the question of origin, the authors conclude that

"the evidence seems to be that the ellipsoidal structure is both subaqueous and subaerial in its development, that it is produced by the rolling of the blocks developed during the flow of the lava as a result of cooling, and that its development is therefore determined by the speed of flow and the rate of cooling, which in turn may be affected by entrance into water."

The interbedding of the basaltic flows with subaqueous sediments in the

⁷⁵ C. K. Leith: The Mesabi iron-bearing district of Minnesota. Monograph U. S. Geol. Survey, vol. xliii, 1903, p. 65.

⁷⁶ C. R. Van Hise and C. K. Leith: The geology of the Lake Superior region. Monograph U. S. Geol. Survey, vol. lii, 1911, pp. 120, 151, 502, 510-512.

Lake Superior region is regarded as adequate evidence that the ellipsoidal structure is largely of subaqueous origin.

"It should not be assumed, however, that all the ellipsoidal basalts of the Lake Superior region are necessarily subaqueous. The region is a large one, the conditions are varied, the ellipsoidal structures are locally associated with structures ordinarily regarded as of subaerial origin, ellipsoidal structure is known elsewhere to develop subaerially, hence it is rather likely that a part of the structures in the Lake Superior region are of subaerial origin. . . . Qualitatively the evidence favors the subaqueous origin of the major part of the ellipsoidal basalts."

Idaho.—Structures found in some of the basalts of the Snake River plains in Idaho seem to be comparable in many respects with pillow lavas, although whether any of these are actually identical with pillow structure, and if so to what extent they have been developed, must await more detailed studies for determination. Russell⁷⁷ described a series of seven parasitic cones that were formed on a bare corrugated lava stream near its source. They are steep-sided and regular and range from 15 to 60 feet in height. They are composed principally of "rough ball-like masses of highly vesicular or scoriaceous lava" 8 to 14 inches in diameter and plastic enough to adhere to one another.

Russell found that two sheets near Hagerman showed contrasts between the upper and lower portions, the upper and central parts of the flows being compact or moderately vesicular, while the lower is open in texture and composed of irregular fragments, some extremely rough on the surface and open and cellular within, like "a mass of irregular twigs of glassy lava compressed into a moderately compact mass." There were also many rounded masses "resembling a pillow folded on itself," the lower surfaces of which are flat or concave from being molded on those beneath. "These folded masses clearly indicate a rolling up of the still plastic lava." There were also "oval or nearly spherical boulder-like masses from a few inches to 2 or more feet in diameter, which are excessively hard and compact." The inner portions of these consist of stony basalt with kernels of olivine and the surfaces are coated with black glass 1 to 2 inches thick. Both the spheroidal and the pillow-like masses are embedded in a coarse breccia of irregular glassy fragments.

"All of the facts enumerated unite in indicating that the lava while yet molten entered water and was quickly cooled, hardening to a glass, and that the steam generated blew the still plastic material into shreds and excessively irregular branching forms. As the upper surfaces of the lava sheets are not

⁷⁷I. C. Russell: Geology and water resources of the Snake River plains of Idaho, Bull. U. S. Geol. Survey, No. 199, 1902, pp. 76-98, 113-117.

glassy and do not show the other characteristics referred to, it appears that the water which the still hot lava entered was shallow."

In the Snake River Canyon, 1 mile above Salmon River, a brecciated and torn lava contains masses of stratified sand and clay up to 5 or 6 feet in diameter. In other places streams 30 to 40 feet thick rest on thinly laminated white sandy clay, evidently lake bottom, without disturbing it. The bottom is glassy and contains a few masses of the clay, however, and is vesicular from the steam generated.

California.—Ransome⁷⁸ first described the pillow structure in the eruptive rocks of Point Bonita, near San Francisco, California (plate 18, figure 1), which include a glassy and in part porphyritic spheroidal basalt composed of rounded, flattened, bale-like, pillow-like, and variously twisted forms. Many of the masses are elongated and bolster-like, with their longest axes arranged roughly parallel. Dark green amygdules are numerous, increasing in size and number toward the center, and these spongy central portions often weather out, leaving empty shells. Dimensions range up to 3 and even 5 feet in diameter, and the masses are molded on each other with crushed and sheared material between, so that no empty spaces remain.

The author considers it "evident that we are dealing with a structure taken on by the lava at the time of its original fluidity and movement. It is essentially a flow phenomenon." It is compared with ropy pahoehoe, but is thought to have had greater viscosity and more sluggish movement, causing the rope-like forms to thicken up and shorten.

"In brief then it is supposed that the spheroidal basalt of Point Bonita flowed as a viscous pahoehoe, one sluggish outwelling of lava being piled upon another to form the whole mass of the flow."

Winchell,⁷⁹ commenting editorially on Ransome's description of the Point Bonita rocks, contended that the spheroidal basalt is of pyroclastic origin and not essentially different from the overlying bed of tuff.

Small igneous masses with spheroidal structure on Angel Island were regarded by Ransome⁸⁰ as apophyses from the same magma that formed the neighboring sill of fourchite. Hence it was thought that the pillow structure is not rigidly restricted to surface flows, but these masses "must have been erupted under very nearly surface conditions." The rock con-

⁷⁸ F. L. Ransome: The eruptive rocks of Point Bonita. Bull. Dept. of Geol., Univ. of Cal., vol. i, 1893, pp. 71-113.

⁷⁹ N. H. Winchell: Am. Geol., vol. xiv, 1894, pp. 321-326.

⁸⁰ F. L. Ransome: The geology of Angel Island. Bull. Dept. of Geol., Univ. of Cal., vol. i, 1894, pp. 193-234.

tains inclusions of red and green radiolarian cherts, through which it breaks.

Fairbanks⁸¹ has described a basalt from Point Sal, near San Francisco, which consists of elongated ropy masses packed over each other in all conceivable positions. A rude parallelism is apparent at one exposure, and some of the masses approximate the spherical form, with diameters ranging from a few inches to 3 feet. In many places also this structure is not sharply differentiated from the structureless basalt. The outer portions of the masses are more compact and have smaller amygdules than the inner, and hence they often weather out hollow.

Lawson⁸² regards all the variolitic spheroidal basalts and diabases of the region around San Francisco Bay (plate 18, figures 1 and 2) as intrusives cutting the Franciscan series. These rocks occur at many places within the area of the four quadrangles included in the San Francisco Folio.

"They are of irregular shape, they include no clean-cut dikes or intrusive sills, and their exposed contacts with the rocks they intrude are generally irregular and jagged. Fragments of the incasing rock, especially of the radiolarian cherts, are abundant at the contacts, where the chert is usually baked to a bright vermilion-red and its structure is in some places also greatly changed. Some inclusions show evidence of partial resorption. The spheroidal structure of these intrusive rocks is clearly revealed only on sea cliffs, as at Hunter Point and Point Bonita, but may also be detected in numerous road cuttings and on natural exposures on hillsides. On sea-cliff exposures the rock presents the appearance of an irregular pile of filled sacks, each sack having its rotundity deformed by contact with its neighbor. Each of these sack-like or ellipsoidal masses measures about 3 feet in its longest and about 1 foot in its shortest diameter. The rock between the ellipsoids is usually more decomposed than that elsewhere and so weathers out easily under the action of the waves, leaving the more resistant ellipsoids prominent. Some of the ellipsoids are vesicular, others are variolitic, and still others are both. The cause of this peculiar structure and the mode of its development are not yet understood."

Alaska.—Grant and Higgins⁸³ have described the ellipsoidal greenstones of the Orca group (Mesozoic) at Prince William Sound, Alaska (plate 19, figures 1 and 2), in which the spheroidal masses range from a few inches to 10 feet in diameter. In many places these bodies make up

⁸¹ H. W. Fairbanks: The geology of Point Sal. Bull. Dept. of Geol., Univ. of Cal., vol. ii, 1896, pp. 1-92.

⁸² A. C. Lawson: San Francisco Folio, U. S. Geol. Survey. I am greatly indebted to the Director of the Survey for permission to consult the proofs of this folio in advance of publication.

⁸³ U. S. Grant and D. F. Higgins: Reconnaissance of the geology and mineral resources of Prince William Sound, Alaska. Bull. U. S. Geol. Survey, No. 443, 1910, pp. 21, 26, 51, 52.

nearly the entire flow. Between them is a softer greenish, locally schistose material, the origin of which is not clear. The masses are commonly somewhat flattened parallel to the dip of the flows, which, in some examples at least, appears to be due to the pressure of one ellipsoid on another before they had completely solidified. Some of the masses are united by small necks (plate 19, figure 1) ; some broken ones show a radial jointing.

"The main volcanic activity seems to have taken place near the shore line of the Orca Sea, while further out sediments were being deposited, and finally sedimentation became the prominent phenomenon even near the shore line."

The characteristic feature of these rocks in the Ellamar district, where they form thick accumulations of flows, is the "abundance of beds in which the greenstone consists of ellipsoidal forms."⁸⁴

"Ellipsoidal greenstones have generally been considered to indicate that the basic lava flows from which they were formed were poured out upon the bottom of a body of water, and that the flowing and cooling of the lavas under water induced this unusual type of parting into ellipsoidal or spheroidal forms. Many facts which can not be discussed here point to the conclusion that these greenstones were extruded upon the sea bottom, and that the deposition of the muds which formed the slates continued during the intermissions between the separate flows."

Capps⁸⁵ further defines the greenstone member of the Orca group as consisting of "a number of lava flows which were intercalated between the slate and graywacke beds, but which did not stop their deposition," and hence many beds of slate and graywacke were laid down between the separate flows. The ellipsoids at the base of a flow are flattened at the bottom, but rounded on the other sides, and the material between the lower ellipsoids is the same as that of the underlying slates. The bottom of a flow is flat and conformable with the stratification ; but the top presents a very different appearance, "consisting of a succession of domes, resembling the surface of a magnified cobblestone pavement, the surfaces of the ellipsoids representing the cobblestones." The mud next deposited takes the shape of the irregular lava surface. These surfaces show no sign of weathering or erosion, and this is thought to add weight to the conclusion that the lavas and interbedded sediments were deposited successively under water.

Maine.—In 1896 Smith⁸⁶ described the dense amygdaloidal diabases

⁸⁴ S. R. Capps and B. L. Johnson : Mineral deposits of the Ellamar district. Bull. U. S. Geol. Survey, No. 542, 1913, pp. 95, 96.

⁸⁵ S. R. Capps : Report on the Ellamar district, Alaska. In manuscript, to which I am permitted to refer by courtesy of the Director of the U. S. Geological Survey.

⁸⁶ G. O. Smith : The geology of the Fox Islands, Maine. Dissertation, Johns Hopkins Univ., 1896, pp. 16-19.

of North Haven Island, Penobscot Bay, Maine, which are characterized by the same type of pillow structure as the greenstones of Saxony and the Lake Superior region.

"Seen in cross section only, as on a glaciated surface or low cliff on the shore, the rock appears to be divided into irregular ellipsoidal masses or lenses from a few inches to two feet in major diameter. These masses of compact rock are embedded in a matrix which is a schistose phase of the same rock, and the less resistance of the matrix to weathering agencies gives prominence to the structure, the oval sections often being surrounded by narrow crevices."

Dathe's hypothesis of contractional parting during consolidation of the flow was considered inapplicable, since it would fail to account for the schistose matrix between the masses. Transition phases between the ellipsoidal rock and the normal diabase with columnar structure were clearly observed, and hence a purely dynamic origin, that of brecciation *in situ*, was not entirely satisfactory. "In the present case, however, the origin seems to have been compound, a true contraction parting modified by dynamic action."

"At one locality these structures (columnar and ellipsoidal) can be compared with the concentric weathering in a dike, and the contrast is such as to allow no confusion of the three different structures."

Gregory⁸⁷ found among the andesites of the Aroostook area, Maine, "black, rusty-looking, spheroidal and elliptical masses of lava, one to two feet in diameter," strewn over the surface, and solid ledges composed of similar forms whose outlines are well displayed by weathering. The masses are amygdaloidal at the surface and denser within and are cemented together by a coarse breccia of glassy material and igneous rock of the same character as the spheroids. Flow into water or watery silt, as supposed for other structures of this kind, may, the author thinks, be the explanation of these; but, on the other hand, they may be "the ropy rolling surface at the front of a lava flow."

Massachusetts.—Crosby⁸⁸ has described the melaphyre flows of Nantasket, Massachusetts, in which a compact greenish matrix incloses irregularly rounded amygdaloidal masses from 2 inches to 2 feet in their longest diameters. The amygdules are arranged in concentric lines or zones parallel with the exterior, the largest ones being either near the surface or near the center. The surfaces of some of the sheets show rounded multidomical protuberances or swellings from 1 to 4 feet in

⁸⁷ H. E. Gregory: Andesites of the Aroostook volcanic area of Maine. *Am. Jour. Sci.*, 4th ser., vol. viii, 1899, pp. 359-369.

⁸⁸ W. O. Crosby: Geology of the Boston Basin. *Occas. Papers Bost. Soc. Nat. Hist.*, iv, vol. i, pt. 1, 1893, pp. 50-53.

diameter, the actual boundaries of which extend below the surface of the flow. These are not products of erosion and, according to the author, must be regarded as original structures. One flow is described as consisting of rounded pseudobombs thickly and uniformly scattered through the middle and upper parts of the sheet and wanting at the bottom. The author offers the tentative explanation that "during the flow of the lava layers and crusts were, by the unequal flowing and revolving motions, broken up and the fragments rounded into the forms we now see."

Emerson⁸⁹ has described the Triassic basalt sheet of Deerfield, Massachusetts, a portion of which had formerly been regarded as an agglomerate, the masses being separated in part by stringers of sandstone like that on which the sheet rests.

"Many of the blocks have rows of these cavities [steam vesicles] around their borders in whole or in part, and these cavities are tubular at times and closely set at right angles to the fissure which separates the block from its neighbor. . . . [This arrangement] shows that the slow expansion of the steam was effective after the mass had cracked into great blocks."

Some of the blocks higher up seem to have been invaded by later lava, which, it was thought, sheathed the blocks and partially remelted them into a spheroidal form. Other masses are separated by an admixture of glass fragments and red sand. At the tower of Greenfield there is no basal bed of normal trap;

"but the whole mass was cooled nearly to the crystallizing point when the sand rose up into it at almost equal intervals, and the streams of sand and glass breccia formed by the water rise in great streaks or 'schlieren,' anastomose, and pass with fluidal structure around the great rounded blocks of the normal trap. . . . The rounded bomb-like masses and the compact crystalline trap which are contained in this breccia grade superficially through hyalopilitic trap into the green glass, and while compact at the center are toward the surface full of radiating steam pores. . . . Among the blocks are many long sheets and rounded masses connected by narrow necks, which could not have been blown into the air and have fallen as common bombs."

Typical pillow lavas are shown in the illustrations, one of which I am permitted to reproduce by courtesy of Professor Emerson (see plate 24).

Connecticut.—Emerson⁹⁰ compares the structures described in the preceding paragraphs with similar beds near Meriden, Connecticut, and attributes both to a rapid submarine flow of lava, while steam from the underlying water-soaked sediments broke the bottom crust and the mud

⁸⁹ B. K. Emerson: Diabase pitchstone and mud inclosures of the Triassic trap of New England. Bull. Geol. Soc. Am., vol. 8, 1897, pp. 59-86. Also Geology of Old Hampshire County, Massachusetts. Monograph U. S. Geol. Survey, vol. xxix, 1898, pp. 418-431.

⁹⁰ B. K. Emerson: Loc. cit.



FIGURE 1.—PILLOWY SURFACES IN ELLIPSOIDAL GREENSTONE OF THE ORCA GROUP (MESOZOIC)

The lava flow has been exposed by waves near Rocky Point, Prince William Sound, Alaska. Masses range from a few inches to 10 feet in diameter. Photograph from the U. S. Geological Survey. Bulletin 443, plate viii-A.

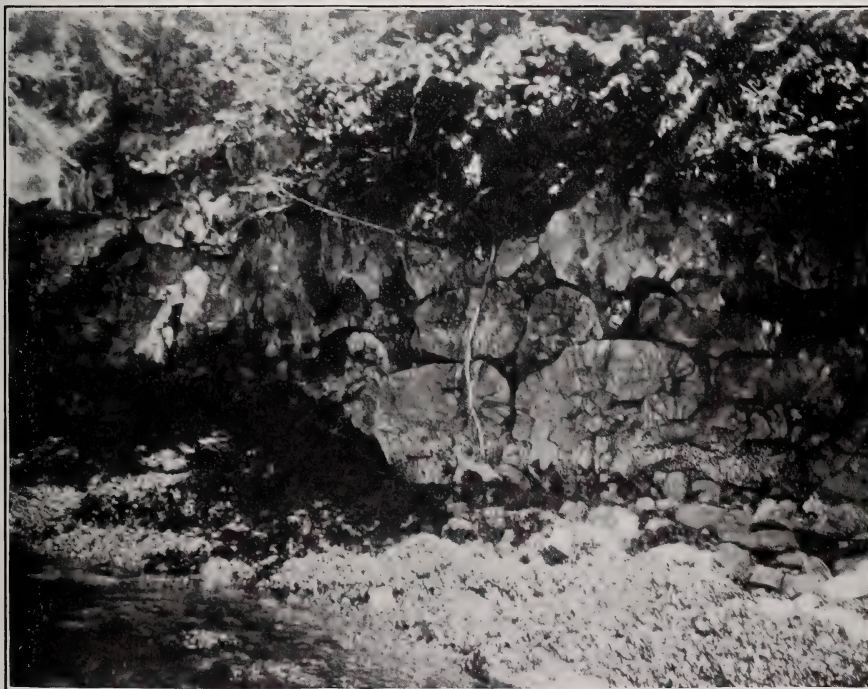


FIGURE 2.—CROSS-SECTION SHOWING RADIAL JOINTING OF THE PILLOWS AT THE SAME LOCALITY
Masses range from a few inches to 10 feet in diameter. Photograph from the U. S. Geological Survey. Bulletin 443, plate viii-B

PILLOW SURFACES OF ELLIPSOIDAL GREENSTONE AND CROSS-SECTION OF RADIAL JOINTING OF PILLOW LAVA

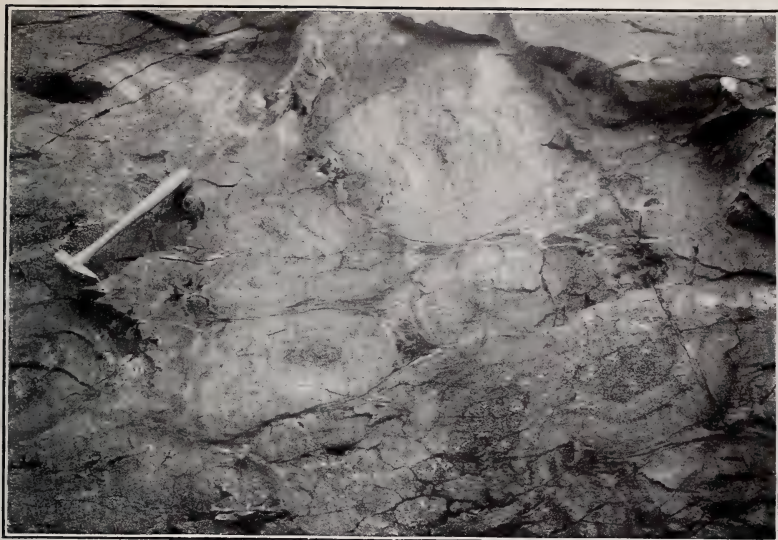


FIGURE 1.—PILLOW LAVA

Showing concentric layers of amygdules and calcite filling the interstices between the pillows. The locality is Pentire Head, St. Minver, north coast of Cornwall, England. Photograph from the Geological Survey of Great Britain.

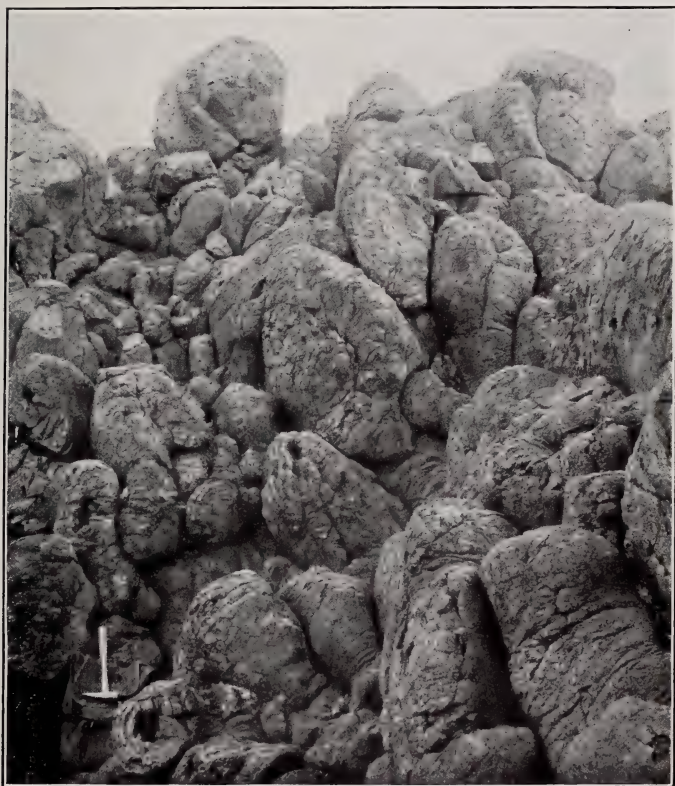


FIGURE 2.—PILLOW "DIABASE"

The locality is on the shore 2 1/3 miles south of Ballantrae, Ayrshire, Scotland. Photograph from the Geological Survey of Great Britain

PILLOW LAVA AND PILLOW "DIABASE"

frothed up into the liquid lava, carrying with it blocks of the basal bed. "These blocks graduate outwardly into glass, and so have been rounded in place by remelting." The whole mass of this structure is 30 to 70 feet thick for several miles and is covered everywhere by normal trap. There is also normal trap beneath the "breccia" in many places, so that the latter "must have been formed in the midst of the sheet itself."

Davis and Whipple⁹¹ had previously described this structure near Meriden, where the base of the sheet for a thickness of 20 feet or more contained "oval and discoidal areas of close-grained trap that we have interpreted as volcanic bombs," in a matrix consisting of trap fragments and volcanic glass, considered to be lapilli. The "bombs" were found "remarkable for their nonvesicular character and their compact, uniform texture from center to surface."

New Jersey.—Rounded masses of lava on the northwestern slope of the First Watchung Mountain trap sheet at Glenside Park (formerly Feltville), 2 miles northeast of Scotch Plains (figure 2), were described by Russell⁹² in 1878 and compared to the "friction-breccias" of Von Cotta, as he then considered the trap to be intrusive. The masses were found to have a concentric structure, with a slaggy and scoriaceous exterior, and the spaces were filled with angular fragments of greenish rock bound together with reddish cement like the overlying shale. Davis⁹³ found the structure to consist of

"a number of oval masses of trap up to 2 feet or more in diameter, contained in a peculiar red and black matrix. The trap masses vary in their texture and color with the distance from their surface; the outer part is black and dense, then amygdaloidal for a few inches with concentric bands of color, and rather dense near the center."

Darton⁹⁴ also described this structure in 1890 and in 1908 and Kümmel⁹⁵ in 1897.

In 1907 the writer described the structure at Paterson, New Jersey, and vicinity (plates 15 and 16) as

⁹¹ W. M. Davis and C. L. Whipple: The intrusive and extrusive trap sheets of the Connecticut Valley. *Bull. Mus. Comp. Zool. Harvard*, vol. xvi (Geol. Ser., vol. ii), 1889, pp. 99-138.

⁹² I. C. Russell: On the intrusive nature of the Triassic trap sheets of New Jersey. *Am. Jour. Sci.* (3), vol. xv, 1878, pp. 277-280.

⁹³ W. M. Davis: On the relations of the Triassic traps and sandstones of the eastern United States. *Bull. Mus. Comp. Zool. Harvard*, vol. vii, 1883, p. 274.

⁹⁴ N. H. Darton: The relations of the traps of the Newark system in the New Jersey region. *Bull. U. S. Geol. Survey*, No. 67, 1890, pp. 26-28; also *Passaic Folio* (U. S. Geol. Survey, No. 157; *Geol. Survey of N. J.*, No. 1), 1908, p. 9.

⁹⁵ H. B. Kümmel: The Newark system or red sandstone belt. *Ann. Rept. State Geologist of N. J. for 1897*, pp. 82, 83.

"pahoehoe or ropy rolling surfaces produced by the flowing of the viscous lava . . . the rounded billowy forms of which are often covered with dark glass one-half an inch to one inch thick. Often these ropy glassy surfaces are also vesicular or amygdaloidal. In some of the quarries such rounded forms are superimposed to a depth of 50 to 75 feet and the cavernous spaces between them have been partially filled with calcite, quartz, and zeolites."⁹⁶

Fenner⁹⁷ also described the pillow structure at Paterson as pahoehoe, and ascribed its origin to the flow of lava into shallow water with muddy bottom. First a thin flow caused a violent agitation and mixing of the lava and mud; successive spurts and tongues of fused material, chilled suddenly by steam rising around them, built up the structure of boulder-like forms. The original surface water was quickly driven off, but the wet sediments continued to furnish steam, some of which entered the lava and made it vesicular, but most of it worked its way around the masses and quickly cooled the crusts to glass.

"The jets and tongues of fused material seem to have assumed the consistency of a thick syrup and instead of spreading laterally they solidified in smoothly rounded boulder-like masses, having considerable similarity to the 'pahoehoe' of Hawaiian flows. . . . The pasty character of the fluid and its sluggish movements are well attested in the billowy forms presented when quarrying operations have attacked bodies of trap of this character. The rounded forms are sometimes built up to a thickness of 60-70 feet. The interior of the boulders cooled with sufficient slowness to permit the basalt to crystallize with normal texture, but each is sheathed with a crust of glass (tachylite) varying from an inch to several inches in thickness, having often a laminated structure. . . . The crusts frequently present a shattered appearance due to the sudden chill which they experienced, and at times pockets among the boulders are filled with considerable masses of breccia of this nature."

Pillow structure in New Jersey, some examples of which have been described briefly in the preceding paragraphs, I have found typically developed in the Triassic (Newark) basalts of both First and Second Watchung Mountains. In First Mountain the structure may be traced in surface outcrops, quarries, and street and railway cuttings from the corner of Hamburg Avenue and Jane Street, one-half mile northwest of Passaic Falls, in Paterson, in a slightly curved belt near the middle of the trap outcrop, in a direction about south 25° west to the trap quarry

⁹⁶ J. Volney Lewis: Petrography of the Newark igneous rocks of New Jersey. *Ann. Rept. State Geologist of N. J.* for 1907, p. 152.

⁹⁷ C. N. Fenner: Features indicative of physiographic conditions prevailing at the time of the trap extrusions in New Jersey. *Jour. Geol.*, vol. xvi, 1908, pp. 299-327; also *The Watchung basalt and the paragenesis of its zeolites and other secondary minerals. Annals N. Y. Acad. Sci.*, vol. xx, 1910, pp. 99, 100.

near the railroad station at Great Notch, a distance of four miles. The superficial exposures of pillowy basalt along this course vary from 100 or 200 feet to more than 1,000 feet in width. There is no indication of an ending of the structure at either extremity of this belt, but the thick and almost continuous covering of glacial drift for several miles northeast of Paterson and southwest of Great Notch has thus far prevented the identification of the structure beyond the points named.

Pillow structure is exposed in great perfection of development in the trap quarries of West Paterson and Great Notch (plates 15, 16, and 17, figure 1), where it extends to the full depth of the quarries, and the bottom has not been reached. Fifteen miles farther southwest a precisely similar structure has been exposed to only a shallow depth in the same basalt sheet (but at the upper surface instead of near the middle) by a small ravine and the old prospecting pits locally known as the "copper mine," near Glenside Park (formerly Feltville), 2 miles northeast of Scotch Plains (figure 2, page 628).

In contrast with these occurrences, the pillows of Second Mountain occur at the bottom of the great basalt sheet. At Little Falls they are exposed at the northeast corner of the new concrete reservoir of the East Jersey Water Company, and may be seen at short intervals northward along the eastern border of the trap for more than half a mile. The pillows attain maximum diameters of 2 to 3 feet and, again in contrast with those of First Mountain, are for the most part markedly vesicular. They are coated with the characteristic glassy (tachylitic) crust and form accumulations 10 to 20 feet thick along the old quarry walls and in the cliffs. In places they form the bottom of the sheet next to the underlying red sandstone, which was formerly quarried extensively along this contact, and elsewhere they rise 10 feet or more above the base, the latter consisting in such places of normal basalt jointed into small wedgy and splintery columns.

The exposures at West Paterson and Great Notch are particularly fine. In grading the streets of Paterson the rock has been cut along McBride Avenue from Rockland Street to Howard Street (near the right bank of the Passaic River, three-eighths of a mile above the falls), exposing excellent examples of pillow structure with nearly circular cross-sections in places (plate 15), but also showing ellipsoidal and long-drawn-out bolster-like masses. The common interstitial tachylite breccia, with calcite, quartz, zeolites, etcetera, has been weathered out so completely as to exhibit very clearly the spheroidal, boulder-like appearance of the pillows. Later excavations have modified the exposure along this street somewhat, but it still shows both the curved surfaces and the cross-sections of typical

pillows of a wide range of form, and some of these show the short necks by which they are joined together.

Three-eighths of a mile south of the river and just above the West Paterson station of the Delaware, Lackawanna and Western Railroad, a large quarry in the trap rock shows pillow structure (plate 16) constituting the whole of the west and south walls of the quarry, a thickness ranging from 50 to 75 feet, and also a part of the east wall has the same structure. Northward along the east wall, however, the solid lava, about 20 feet thick, with somewhat irregular jointing, underlies the pillowy rock, and beneath this, in turn, the bottom part of the wall and the adjacent bed of the quarry consist of extremely vesicular lava in somewhat rounded and irregular masses up to 8 or 10 feet in diameter and intimately mingled with a matrix of red mud, which here consists of a mix-



FIGURE 1.—*Geologic Cross-section of First Watchung Mountain*

Showing the position of quarries and railroad cut with pillow lava. Paterson, New Jersey. Horizontal and vertical scale the same

ture of clay and very fine quartz sand. The masses in this portion are least vesicular at the center and extremely scoriaceous and spongy at the surface, where they are mingled with and stained by the red mud. Northward this vesicular mass drops below the bed of the quarry and solid lava constitutes the whole of the depth at the northeast corner, with the lowermost 10 or 15 feet jointed in regular columns. About 500 feet westward an older and somewhat smaller quarry beside the railroad shows the pillow structure in its southern and eastern walls. Interbedded massive basalt overlies this in the western wall, but pillow structure again occurs, at a higher horizon, in the railroad cut immediately northwest of the quarry.

Most of the pillows are circular or elliptical in cross-section and range from 1 to 2 feet in diameter, although both smaller and larger individuals are found. They vary in shape from spheroidal to ellipsoidal and somewhat more elongated bolster-like and irregular forms, but in general the structure is prevaillingly ellipsoidal and remarkably regular. The individual masses show little or no distortion at the points of contact with one

another. Each one is covered with a sheath of basic glass (tachylite), varying from a thin film to an inch or more in thickness, and thin sections show that this passes gradually into the holocrystalline mass of the interior. The glass is very brittle and has a tendency to shell off parallel to the surface on exposure to the weather or when struck with a hammer. Hence it is very difficult to collect a specimen of the crystalline rock with the glass still attached to it.

In the First Mountain pillows, in striking contrast with those of Second Mountain, there are few amygdules, and these are small and chiefly near the surface coating of glass. On the other hand, many of the masses have a central "pipe" or cavity from 1 to 6 or 8 inches in diameter, many of these being flattened parallel to the bedding of the sedimentaries (plate 17, figure 1). Radial columnar jointing is a common characteristic of the spheroids and is especially well shown in weathered sections, as in the upper portions of quarry walls. The spaces between the masses are partly filled (in some places entirely so) with angular fragments of glass like that which coats the individual pillows. This has generally been cemented into a breccia by the deposition of quartz, calcite, a great variety of zeolites, and many other less common minerals.

At Great Notch (plate 17, figure 1) a structure in every way similar to that at West Paterson forms the south wall of the trap quarry near the railroad station, where a thickness of 40 to 50 feet has been exposed.

At Glenside Park (Feltville) the pillow structure outcrops one-fourth of a mile east of the bridge in the narrow ravine of a brook that drains the northwestern slope of First Mountain. Spheroids and irregular pillows are exposed in the bottom of the ravine and in several old prospecting pits, locally known as "the copper mine," while the banks of the brook show a similar structure and its relations to the overlying shale (figure 2). The interstitial material is a mixture of shale and angular fragments of glass. The lava here is somewhat vesicular, many of the masses having elongated tubular vesicles, 3 to 4 inches long and one-fourth of an inch or less in diameter, set at right angles to their outer surfaces. Most of these tubes are filled with chlorite, calcite, quartz, and zeolites. Russell⁹⁸ reported the finding of some that contained a brilliant jet-black bitumen.

At Glenside Park (Feltville) the pillow lava occurs immediately at the upper surface of the flow (see figure 2) and extends downward to an undetermined depth. A maximum depth of 10 or 12 feet is visible in the banks and the old prospecting pits, and the structure is typically developed in the bed of the brook. The overlying shales rest on the uneroded

⁹⁸ I. C. Russell: The occurrence of a solid hydrocarbon in the eruptive rocks of New Jersey. *Am. Jour. Sci.* (3), vol. xvi, 1878, pp. 112-114.

surface of the flow, as shown by the unoxidized condition and the dense enamel-like character of the undulating pillowy surface. The flow occurred in a broad intermont valley, or bolson, of continental deposition and was soon buried in the accumulating sediments.⁹⁹

At Great Notch the situation of the quarries near the middle of the trap outcrop shows that they are also about the middle of the sheet, and the same condition holds northward to Paterson. The quarries at the latter place may be somewhat below the middle of the sheet, but they are still well above its base, as shown by figure 1, which has been constructed to true scale from the most accurate data obtainable. I do not believe it possible to consider the scoriaceous muddy lava encountered at one point in the floor of the quarry at West Paterson as the base of the sheet, although Fenner¹⁰⁰ has so interpreted it. In attributing the origin of the pillows to the influence of this mud and possibly an accompanying body of water, Fenner further overlooked the very important fact that there is

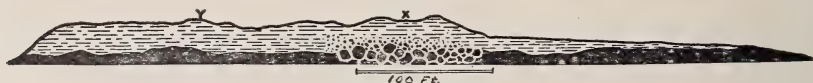


FIGURE 2.—*Diagrammatic Cross-section at Glenside Park, New Jersey*

Showing relations between the massive basalt, pillow basalt, and the overlying shale in a ravine one-fourth of a mile east of the bridge at Glenside Park (Feltville), New Jersey. Modified after Darton. Bulletin of the U. S. Geological Survey, number 67.

a thickness of 20 to 30 feet of massive lava between the muddy scoria and the pillows. In this there is no trace of mud, nor in the overlying pillow lava, and it is difficult to conceive of any possible genetic connection between them. Somewhat similar structural relations seem to exist at Great Notch also. The aqueduct tunnel encountered much muddy, cindery lava, as shown by the refuse dumps; but the quarry, which lies about 100 feet above the tunnel, shows characteristic pillowy structure without admixture of mud. It is significant that here also the old quarry beside the railroad, a few hundred feet west of the present quarry and at a higher horizon, exposed a like scoriaceous muddy phase of the basalt. This lies well above the pillows and, like that below them, must be regarded as entirely independent.

We are thus placed in the dilemma that Emerson faced at Greenfield, Massachusetts, where he ascribed the "breccia" (pillow lava) beds to the influence of the underlying wet sediment; but in many places normal

⁹⁹ J. Volney Lewis: The origin and relations of the Newark rocks. *Ann. Rept. Geol. Survey of New Jersey for 1906*, pp. 97-129; Charles Schuchert: *Bull. Geol. Soc. Am.*, vol. 20, 1910, pp. 438, 578, 579; Joseph Barrell: *Am. Jour. Sci.*, vol. xxxvi, 1913, p. 438.

¹⁰⁰ C. N. Fenner; *Annals N. Y. Acad. Sci.*, vol. xx, 1910, p. 99.

trap also occurs beneath the "breccia," "so that the latter must have been formed in the midst of the sheet itself,"¹⁰¹ by what process and through what connection with the underlying wet sediment the author did not undertake to explain.

I have elsewhere presented evidence tending to show that the basalt flows did not well out in a single vast eruption for each sheet, but that in every case the great thickness was built up by a succession of smaller flows or pulsations which spread themselves one on another.¹⁰² Here and there some of these subordinate flows encountered local pools of water or saturated deposits of mud on the undulating surface of the underlying lava, and the result was a frothing up of a small portion of the fresh flow at the contact and an intimate mixture of the mud with the vesicular mass. At Paterson one of these was overflowed with clean, solid basalt before the formation of pillow lava began, and throughout the great thickness of this zeolite-studded spheroidal mass there is no recognizable trace of the underlying mud. In fact the pillows, almost entirely free from vesicles and amygdules, are in striking contrast with the extremely scoriaceous mass with which the mud is mingled.

On the other hand, the pillow lava of Second Mountain is highly vesicular, but is equally free from admixture of mud, although in many places it is developed in immediate contact with the underlying sediments, and the structure lies very near the bottom wherever it has been observed.

CHRONOLOGICAL TABLE OF PILLOW LAVAS, PAHOEHOE, AND AA

The descriptions that have been referred to in the preceding pages, together with certain pertinent observations on the formation of pahoehoe and aa lavas, have been listed in chronological order in the following table. Theories of origin, discussed or implied, are briefly indicated in the last column.

Pillow lavas are to be understood unless otherwise indicated.

¹⁰¹ B. K. Emerson: *Geology of Old Hampshire County, Massachusetts*. Monograph U. S. Geol. Survey, vol. xxix, 1898, p. 424.

¹⁰² Ann. Rept. of State Geologist of N. J. for 1907, p. 150.

Date	Author	Locality or subject	Theory of origin
1834	C. F. Naumann.	Hainichen, Saxony.....	Conglomerate modified by dynamic action.
1846	A. Delesse.....	Spheroidal structure.....	Concretion during crystallization.
1848	N. Whitley.....	Port Isaac, Cornwall.....	"As if it had rolled down a declivity."
1865	H. Credner.....	Andreasberg, Harz.	
1869	Jas. Thomson.....	Columnar jointing and spheroidal structure.	Rejects concretionary hypothesis.
1870	R. Ludwig.....	Schelderwalde, Hesse.....	Flow phenomena.
1871	C. F. Naumann.....	Hainichen, Saxony.....	Brecciation <i>in situ</i> .
1876	G. R. Credner.....	Hainichen, Saxony.....	Brecciation <i>in situ</i> .
1876	T. G. Bonney.....	Spheroidal structure.....	Contraction by cooling.
1878	I. C. Russell.....	Felville, New Jersey.....	Friction breccia.
1879	A. Rothpletz.....	Hainichen, Saxony.....	Movement in jointed rock by orographic pressure.
	F. Hoffmann.....	Schauenstein, Bavaria.....	Direct from fluid lava.
1880	J. Geikie.....	Faroe Islands.....	Spheroidal weathering.
1881	T. G. Bonney.....	Porthdinlleyn, Wales.	
1881	L. Mazzuoli and A. Issel.....	East Liguria, Italy.....	Concretionary.
1881	R. W. Ells.....	North New Brunswick.....	Concretionary.
1883	E. Dathe.....	North Vogtland.....	Direct from fluid lava.
1883	W. M. Davis.....	Felville, New Jersey.	
1884	C. E. Dutton.....	Pahoehoe (Hawaii).....	Small offshoots of highly liquid lava.
		Aa (Hawaii).....	Thick, stiff flow.
1885	K. Dalmer.....	Planitz, Saxony.....	Not result of weathering.
1885	A. C. Lawson.....	Lake of the Woods.....	Apparently concretionary.
1887	A. Denckmann.....	Herborn, Hesse.....	Cooling surfaces of lava.
1887	J. D. Dana.....	Aa and bomb-like masses.....	Both of same origin.
1887	W. L. Green.....	Domical pahoehoe.....	Small, quiet flows forming a tough skin.
1887	W. L. Green.....	Spheroidal lava.....	Dropping from ledge into sea.
1887	D. Zaccagna.....	Monte Viso, Western Alps.....	Spheroidal weathering.
1888	J. F. Blake.....	Anglesey.....	Produced by cooling.



FIGURE 1.—PILLOW LAVA

Showing concentric arrangement of vesicles and interstitial limestone, 3 miles southwest of Tayvallich, Argyll, Scotland. Photograph from the Geological Survey of Great Britain



FIGURE 2.—LONGITUDINAL AND TRANSVERSE SECTIONS OF PILLOW LAVA

Showing concentric arrangement of vesicles. The exposure is near North Ardbeg, Argyll, Scotland. Photograph from the Geological Survey of Great Britain

PILLOW LAVA FEATURES

Date	Author	Locality or subject	Theory of origin
1889	R. Brauns.....	Quotshausen, Hesse.....	Flow surface phenomena.
1889	W. M. Davis and C. L. Whipple..	Meriden, Connecticut.....	Agglomerate of bombs.
1890	G. A. J. Cole and J. W. Gregory.	Mont Genève.....	Movements deep within crater.
1890	G. H. Williams.....	Menominee and Marquette districts..	Dynamic movement in jointed masses.
1890	J. D. Dana.....	Aa (Hawaii).....	Ground moisture rising through the flow.
1890	N. H. Darton.....	Feltville, New Jersey.	
1891	G. A. J. Cole.....	Anglesey	Direct from liquid lava.
1891	J. W. Gregory.....	Fichtelgebirge	Jointing and rolling while semiviscid.
1891	G. Platania and H. J. Johnston- Lavis.....	Acircale, Sicily.....	Injection into submarine silt.
1892	N. H. Winchell.....	Ely, Minnesota.....	Agglomerate of bombs, marine.
1893	H. Fox.....	Mullion Island, Cornwall.	
1893	H. Fox and J. J. H. Teall.....	Mullion Island, Cornwall.....	Submarine flow penetrating sediments.
1893	J. J. H. Teall.....	Pillow lavas.....	Submarine, possibly deep-sea lavas.
1893	C. A. Raisin.....	The Lley, Wales.....	Contraction jointing and secondary invasion of lava.
1893	W. O. Crosby.....	Nantasket, Massachusetts.....	Breaking up of flow in motion.
1893	F. L. Ransome.....	Point Bonita, California.....	Viscous pahoehoe heaped up.
1894	N. H. Winchell.....	Point Bonita, California.....	Pyroclastic.
1894	F. L. Ransome.....	Angel Island, California.....	Intrusion under nearly surface conditions.
1895	N. H. Winchell.....	Lake Superior region.....	Pyroclastics falling into sea.
1896	G. O. Smith.....	Fox Islands, Maine.....	Contraction parting modified by dynamic ac- tion.
1896	H. W. Fairbanks.....	Point Sal, California.	
1897	A. Geikie.....	Great Britain.....	Flow into water or watery silt.
1897	B. K. Emerson.....	Deerfield, Massachusetts.....	Rapid submarine flow.
1897	H. B. Kimmel.....	Feltville, New Jersey.....	Ropy flow surface.
1897	H. L. Smyth.....	Marquette district.....	Mechanical origin.
1898	A. Geikie and A. Strahan.....	North Somerset, England.....	Submarine flow.

Date	Author	Locality or subject	Theory of origin
1899	B. N. Peach, J. Horne, and J. J. H. Teall.....	South of Scotland.	
1899	H. E. Gregory.....	Aroostook, Maine.....	Subaqueous flow, or rolling surface at front of flow.
1899	N. H. Winchell.....	Ely, Minnesota.....	Probably pyroclastic, but problematical.
1899	J. M. Clements.....	Crystal Falls district.....	Breaking up of viscous flow while in motion.
1900	A. Geikie.....	Fife, Scotland.....	Submarine, "rolled along."
1901	A. B. Willmott.....	Michipicoten district.....	Lava flows with "ellipsoidal parting."
1902	E. Greenly.....	Southeast Anglesey.....	Pasty bodies rolled and pressed together.
1902	I. C. Russell.....	Snake River, Idaho.....	Pahoehoe: flow of viscous lava; aa: rapid flow of viscous lava; globular and pillowy: flow into water.
1903	F. Heineck.....	Herborn, Hesse.....	Surface flow phenomena.
1903	A. Geikie.....	Pillow lava.....	"Sudden disruption and chilling" on flowing into water.
1903	B. N. Peach.....	Argyll, Scotland.	
1903	R. A. Daly.....	North Newfoundland.....	Extrusion of basic lava into sea of some depth.
1903	J. M. Clements.....	Vermilion district.....	Rolling of aa lava while still plastic.
1903	C. K. Leith.....	Mesabi district.....	While cooling, perhaps subaqueous.
1904	J. F. Kemp.....	"Spheroidal" (definition).....	Breaking up on cooling, analogous to columnar jointing.
1904	C. L. Morgan, S. H. Reynolds, and W. S. Boulton.....	North Somerset, England.....	Submarine flow implied.
1905	R. D. M. Verbeek.....	Island of Ambon, East Indies.	
1906	R. Brauns.....	Dillenburg, Hesse.....	Flow surface phenomena.
1907	E. Reuning.....	Herborn, etcetera, Hesse.....	Submarine eruption rent asunder and balled-up at contact with water.
1907	W. A. E. Ussher.....	Southeast Cornwall, England.....	"Inrolled interstitial sediment."
1907	J. Volney Lewis.....	Paterson, New Jersey.....	Flow of viscous lava.

Date	Author	Locality or subject	Theory of origin
1908	C. N. Fenner	Paterson, New Jersey	Flow into shallow water with muddy bottom.
1908	C. Reid and H. Dewey	Port Isaac, Cornwall	Submarine "mobile sheet of rolling spheres."
1908	T. Anderson	Northeast Iceland	Pillows forming subaerial secondary cones.
1908	J. S. Flett	Cavernous pillows	Like Pantelleria bombs of 1891.
1909	A. Harker	Pillow lavas	Deep-sea intrusion into soft sediments.
1909	J. P. Iddings	Pillow lavas	Flow phenomena.
1909	C. H. Hitchcock	{ Pahoehoe (Hawaii) Aa lava (Hawaii)	Liquid lava; crust forms quickly.
1909	R. C. Allen	Woman River, Ontario	Nature and origin unknown.
1910	T. Anderson	Matavann, Samoan Islands	Thought to be subaqueous.
1910	C. K. Leith	Hudson Bay	Small flow entering sea in bulbous lobes.
1910	U. S. Grant and D. F. Higgins	Prince William Sound, Alaska	Eruption subaqueous and tidal flats.
1911	H. Dewey and J. S. Flett	Great Britain	Flow in shallow sea near shore.
1911	H. H. Thomas	Pembroke, Wales	Submarine flows.
1911	C. R. Van Hise and C. K. Leith	Lake Superior region	Rolling of blocks developed in the flow by cooling.
1912	C. I. Gardiner and S. H. Reynolds	Kilbride Peninsula, Ireland	Submarine flow.
1912	J. S. Flett and J. B. Hill	The Lizard, Cornwall	Contact with water favored development of pillows.
1912	N. Sundius	Kiruna district, Sweden	Submarine flow.
1913	A. H. Cox and O. T. Jones	North and South Wales	Subaqueous or subaerial pahoehoe.
1913	S. R. Capps and B. L. Johnson	Ellamar district, Alaska	Flow surface phenomena.
1913	A. W. Grabau	Pillow lavas	Apparently connected with "spheroidal state"
1914	F. v. Wolff	Pillow lavas	at contact with water, but not yet clear.
1914	R. A. Daly	Pillow lavas	Submarine flow.
1914	S. R. Capps	Ellamar district, Alaska	Intrusive; origin of structure unknown.
1914	A. C. Lawson	San Francisco, California	

PILLOW LAVA AND SPHEROIDAL STRUCTURE IN GENERAL

In 1866 Lyell¹⁰³ believed globular structure to be recognizable only in decomposing greenstone, basalt, and other trap rocks, but considered it to be a development of an original structure previously invisible, in accordance with the views of Delesse,¹⁰⁴ which he summarizes as follows:

“According to the theory of M. Delesse, the center of each spheroid has been a center of crystallization around which the different minerals of the rock arranged themselves symmetrically during the process of cooling. But it was also, he says, a center of contraction produced by the same cooling. The globular form, therefore, of such spheroids is the combined result of crystallization and contraction.”

In 1869 Thomson¹⁰⁵ stated that prismatic jointing is usually attributed to one or both of the following principles: 1. Prismatic fracture by shrinkage in cooling, like mud or starch in drying. 2. An assumed spheroidal concretionary action of the lava or basalt in solidifying from the molten state. Lyell, Daubeny, Jukes; and others are cited as having advocated the spheroidal concretionary theory, according to which both the longitudinal and cross-joints were supposed to be different parts of the surfaces of spheroids that have grown larger in solidifying till they have met and squeezed themselves together so as to receive flattened faces instead of a rounded form. This theory Thomson believed to be founded on a total mistake.

As late as 1876 Bonney¹⁰⁶ confuses supposedly original spheroidal structure with that produced by weathering, as shown by his illustrations, and ascribes its origin to contraction while cooling.

In connection with Platanina's description of the globular basalts of Acireale, Johnston-Lavis¹⁰⁷ makes the following observation:

“A careful examination of the globular basalts shows that many are not simple globes but rather pear-shaped masses with a narrow neck, which is often absent, having been divided while still fluid. I have lately seen many beautiful examples illustrating this mode of production in my rambles in Iceland; parts of Cape Reykjanes serve as a good example.”

From the association of spheroidal greenstones and diabases with radio-

¹⁰³ Sir Charles Lyell: *Elements of Geology*, 1866, pp. 618, 619.

¹⁰⁴ A. Delesse: *Sur les roches globuleuses*. *Mem. Soc. geol. de France*, 2d ser., tome iv, 1846.

¹⁰⁵ James Thomson: The jointed prismatic structure of the Giant's Causeway and other basaltic rocks. *Belfast Naturalists' Field Club*, 7th Ann. Rept., 1869-1870, pp. 28-34.

¹⁰⁶ T. G. Bonney: On columnar, fissile, and spheroidal structure. *Quar. Jour. Geol. Soc. London*, vol. 32, 1876, pp. 140-154.

¹⁰⁷ H. J. Johnston-Lavis: *The South Italian Volcanoes*. Naples, 1891, p. 43, footnote.

larian cherts in some of the earlier known localities, Teall¹⁰⁸ concluded that the combination is probably characteristic of marine, and possibly of deep-sea, lavas.

Sir Archibald Geikie is also of the opinion that pillow lavas in general have a submarine origin, as expressed in the following:

"Some basic lavas on flowing into water or into a watery silt have assumed a remarkable spheroidal, sack-like, or pillow-like structure, the spheroids being sometimes pressed into shapes like piles of sacks."¹⁰⁹

"They belong to the time when the lava was still in movement and when it separated into globular portions, perhaps by flowing into water or muddy sediment."¹¹⁰

"The origin of these rounded blocks has been ascribed to the sudden disruption and chilling of lava that has flowed into a lake, river, or the sea."¹¹¹

Kemp¹¹² suggests a mode of origin when he defines "spheroidal" as a "descriptive term applied to igneous rocks that break up on cooling into spheroidal masses analogous to basaltic columns."

Harker,¹¹³ in a discussion of the depth at which igneous intrusions occur, says:

"Under submarine conditions where the pressure of a column of water is added to the weight of the rocks, sills may be intruded close to the sea floor. Probably some are forced in along sediments actually in process of deposition in deep water, the distinction between intrusion and extrusion being in such circumstances of little significance. Here belong many of the rocks distinguished by what Sir A. Geikie has styled 'pillow structure.'"

Iddings¹¹⁴ merely suggests that pillow structure is a flow phenomenon, without consideration of its immediate cause:

"Occasionally lava in flowing separates into lumps or small masses that assume rounded forms and when solidified in a closely pressed aggregation have the appearance called pillow structure."

Grabau¹¹⁵ includes pillowy structure among the characteristic surface features of basic lavas. He says:

"While the careful study of these structures in the cases cited has led the observers to the conclusion that such features are reliable as indications of surface flows, yet there are cases in which these surfaces have such an inti-

¹⁰⁸ J. J. H. Teall: On greenstones associated with radiolarian cherts. Trans. Roy. Geol. Soc. Cornwall, vol. xi, 1894, pp. 560-565.

¹⁰⁹ The Ancient Volcanoes of Great Britain. London, 1897, vol. i, p. 25.

¹¹⁰ Textbook of Geology, 4th ed. London, 1903, vol. i, p. 306.

¹¹¹ Textbook, vol. ii, p. 760.

¹¹² J. F. Kemp: A Handbook of Rocks, 3d ed. New York, 1904, p. 224.

¹¹³ A. Harker: The Natural History of Igneous Rocks. New York, 1909, p. 64.

¹¹⁴ J. P. Iddings: Igneous Rocks. New York, 1909, vol. i, p. 300.

¹¹⁵ A. W. Grabau: Principles of Stratigraphy. New York, 1913, pp. 311-317.

mate relation with marine sediments as to suggest the possibility of intrusion. An example of this kind is described by Fox and Teall from the greenstone of the Lizard and Mullion Island, where intimate association with radiolarian cherts suggested that the lava was intruded between the sheets of chert near the surface of the sea bed upon which they were being deposited. This intimate association with radiolarian cherts also found in the Arenig lavas of Great Britain seems at present the only good indication of the probable submarine origin of the lava. So far as the pahoehoe¹¹⁶ type of surface is concerned, it appears to be equally characteristic of subaqueous and subaerial extravasations. That constant and reliable minor differences exist between subaerial and subaqueous lava surfaces is scarcely to be doubted, but at present such differences appear to be unrecognized."

In discussing the pillow or ellipsoidal basalts and the "spilitic suite" of igneous rocks, Daly¹¹⁷ says:

"In most cases their special students have concluded that they represent subaqueous flows. The reason for the balling-up of the lava into relatively small, completely separated pillows or ellipsoids is a physical problem of fascinating difficulty; the structure appears to be connected with the development of the 'spheroidal state' at the contact of water and superheated basic lava, but no one has yet made the matter clear."

Daly rejects Dewey and Flett's¹¹⁸ contention that "the pillow lavas are members of a natural family of igneous rocks, the spilitic suite," and continues:

"In conclusion, the writer believes that the spilitic rocks are pneumatolytic derivatives of normal basaltic magmas and that the modifying gas is chiefly water of *resurgent*, not *juvenile*, origin."

Von Wolff¹¹⁹ classes pillow structure with ropy pahoehoe, which owes its features to slow viscous movement of a smooth-surfaced lava, and the glassy surface coating of which is wrinkled and folded into various forms.

"Fladenlava, Wulstenlava, Taulava, Pahoehoe lava, Helluhraunlava, . . . Diese Lava bewegt sich langsam wie eine zähe, plastische Masse ohne intensive Gasabgabe, welche die erstarrte Oberfläche aufreist. Dieselbe ist von einer zähnen, glasglänzenden Haut bedeckt, die sich bei der Bewegung runzelt, zu Falten, strick- oder tauförmig gedrehten Fladen zusammenschiebt."

Von Wolff refers to the flow-surface features of the Upper Devonian "Deckdiabas," and remarks that it sometimes shows pillowy (wulstig) forms. Reuning's "Kugeldiabas"¹²⁰ is characterized as "eine Art der

¹¹⁶ Including pillowy; the author treats the two terms as synonyms.

¹¹⁷ R. A. Daly: *Igneous Rocks and Their Origin*. New York, 1914, pp. 338-340.

¹¹⁸ H. Dewey and J. S. Flett: On some British pillow lavas and the rocks associated with them. *Geol. Mag.*, vol. viii, 1911, pp. 202-209, 241-248.

¹¹⁹ F. v. Wolff: *Der Vulkanismus*. Stuttgart, 1914, pp. 372, 373.

¹²⁰ E. Reuning: *Neues Jahrb. für Min., etc.*, B. B., vol. xxiv, 1907, pp. 390-459.

"Stromoberfläche" in spite of the fact that extensive fresh excavations showed several flows composed wholly of these forms. Reuning's pointed question whether such a bed 70 meters in thickness can properly be considered the upper flow-surface of "Deckdiabas" is ignored.

THE CONFUSION OF HYPOTHESES

The foregoing summary of the principal available literature concerning pillow lavas will serve to emphasize the aptness of Daly's characterization of the problem: "The reason for the balling-up of the lava into relatively small, completely separated pillows or ellipsoids is a physical problem of fascinating difficulty . . . but no one has yet made the matter clear."¹²¹

From the study of considerably altered and metamorphic greenstones possessing this structure, Rothpletz (1879) and Williams (1890) ascribed the rounded forms, with their schistose chloritic interstitial matter, to the movement of joint blocks on one another under the great pressure of orogenic forces. The fresh and well preserved examples of the structure, however, exclude the possibility of this explanation for the origin of the pillows themselves. Credner (1876) and Russell (1878) attributed them to brecciation *in situ*, and the latter regarded the occurrence at Glenside Park (Feltville), New Jersey, as a friction-breccia developed during intrusion.

Naumann (1834) thought the central Vogtland pillow greenstones were conglomerates, and Winchell (1892, 1894, 1895) viewed the similar greenstones of the Lake Superior region as agglomerates, produced by the falling of bombs and a small amount of finer pyroclastic material into the sea. But in 1899, while still maintaining his former conclusion, Winchell conceded that their nature and origin were problematical.

During the past 15 years all students of this structure have been substantially agreed in regarding it as essentially a flow phenomenon. Many have thought it chiefly if not wholly characteristic of subaqueous flow, and some recognize the possibility of either subaerial or subaqueous origin. When, however, definite processes are sought in their hypotheses—specific explanation of how, for example, a flow of this character, covering many square miles and having a thickness of scores or even hundreds of feet, can be produced from liquid lava—all of them are exceedingly indefinite. Hypotheses that scarcely agree in anything else are strikingly alike in their pervasive vagueness—"the natural result," says Professor

¹²¹ R. A. Daly: *Igneous Rocks and Their Origin*. New York, 1914, p. 338.

Thomson, "of attempting to explain and propound intrinsically untenable views."¹²²

Several observers (Green, 1887; Reid and Dewey, 1908; Daly, 1914) have relied chiefly on a supposed "spheroidal state" which is assumed to exist at the contact of water with a highly heated lava, and in some cases it is evident that a "spheroidal state" of the lava itself is meant. The Port Isaac (Cornwall) pillow lava is a tremendously vesicular and cavernous rock, which Reid and Dewey conceived to have "rolled on cushions of steam" that emanated in part from the magma and in part was generated from the surrounding water. Thus the whole flow, over 200 feet thick, was believed to have advanced like a liquid, the individual spheroids scarcely touching one another until the temperature dropped below the boiling point of the water. The authors assume the individual units were erupted as such, but they do not undertake to explain whether the separation was a part of the process of eruption or was of deeper-seated subterranean origin. Cole and Gregory (1890) thought that such rounded masses had rolled over among themselves deep within an ancient crater and solidified there as pillow lava, subsequent erosion of the upper parts of the volcano having eventually exposed them at the surface.

Assuming the eruption of vast numbers of such lava balls to be possible, their flowlike movement for a short distance in the manner described, on the sea-bottom or even on the land, is perhaps conceivable; but this point is of minor importance compared with the question of their origin, which the hypotheses leave unanswered. Geikie (1903) accounted for their production by the "sudden disruption and chilling" of the lava on flowing into water, and Reuning's (1907) theory is very similar.

Several authors, without appeal to any supposed spheroidal state of the lava (or of the water, which in some mysterious manner induces spheroids in the lava), have imagined such highly exceptional physical conditions of the flow itself as to render their hypotheses scarcely more probable. For example, Gregory (1891), Crosby (1893), Clements (1899, 1903), and Van Hise and Leith (1911) have assumed that the lava might be broken up by contraction-jointing while still possessing a very marked degree of liquidity, so that the supposed joint-blocks developed concentric layers and lines of vesicles, a marked flow-structure parallel to their outer surfaces, and a transition from a glassy exterior to a crystalline interior. That such a supposition could be seriously entertained at all bears eloquent testimony to the "fascinating difficulty" of the problem. The rolling of the angular joint-blocks over one another was supposed to aid in

¹²² James Thomson: *Seventh Ann. Rept. Belfast Naturalists' Field Club, 1869-1870*, p. 28.



FIGURE 1.—VIEW WITHIN THE ACTIVE PIT OF THE CRATER AT HALEMAUMAU, KILAUEA, HAWAII
Newly formed pillows in the foreground illustrate the budding process of development. Photograph by the Geophysical Laboratory



FIGURE 2.—PILLOWY LAVA AT KILAUEA, HAWAII

Illustrating the budding process. Compare this with identical structures at San Francisco and Prince William Sound. Plate 18, figure 2, and plate 19, figure 1. Photograph by the Geophysical Laboratory.

PILLOWY LAVA AT KILAUEA, HAWAII



FIGURE 1.—PILLOW LAVA

Showing the bulbous budding process of development. Compare plate 18, figure 2, and plate 19, figure 1. Crater of Kilauea, Hawaii. Photograph by the Geophysical Laboratory



FIGURE 2.—ORDINARY PAHOEHOE (IN THE DISTANCE) AND PILLOW LAVA CHILLED BY SEA-WATER (IN THE FOREGROUND)

Lava of 1909, volcano of Matavanu, Savaii, Samoan Islands. Photograph by the late Dr. Tempest Anderson. Quarterly Journal of the Geological Society, volume lxxvi, 1910, plate lli

PILLOW LAVA

their rounding, partly owing to internal viscosity and partly by the grinding off of the more brittle surface irregularities.

It is worthy of note that in all the less altered and hence better preserved examples of this structure the interstitial material consists of angular fragments of glass of many sizes, but without rock-flour, and there is no grooving or scratching of the glassy spheroidal surfaces. In short, there is no evidence that appreciable rubbing, rolling, or other mechanical movement has occurred between the individual pillows, and it seems difficult to conceive of any motion that might properly be called a "rolling over among themselves" occurring in such a manner as to leave no trace of it.

Miss Raisin's hypothesis that the pillows are the product of jointing while cooling, modified by a subsequent injection of lava that penetrated the whole mass and coated each individual block with glass, is inconsistent with the occurrence of empty interstitial spaces, so commonly found between the pillows, and also with the zonal arrangement of the interiors and the gradual transition from these into the superficial crust of glass.

In agreeable contrast with most of the others, Johnston-Lavis and Platania (1891) offer a hypothesis that does not seem strained or improbable; and it may well be found, when the characteristic distinctions shall have been worked out, that some of the pillows that are intermingled with the finer marine muds and ooze have been injected into the semifluid and immiscible sediment and thus have formed a sort of giant emulsion. This suggestion is adopted by Harker (1909) as probably of wide application. Obviously, however, such a process would not be possible in coarse sediments nor on the land, and hence many well known examples of pillow lavas would still remain unexplained.

Many writers (Ransome, 1893; Kümmel, 1897; Lewis, 1907; Grabau, 1913) have regarded pillow and ellipsoidal forms as merely variations in the ropy flow structure of viscous pahoehoe, the circumstance of subaerial or subaqueous eruption being by implication of minor importance.

So many references have been made to pahoehoe and aa lavas that descriptions of these types are included here for purposes of comparison (and contrast) with pillow lavas. Descriptions are also appended of such direct observations as are available on the formation of spheroidal and pillow-like bodies in flowing lavas.

FORMATION OF PAHOEHOE LAVA

Dutton¹²³ has described the typical pahoehoe lava of Hawaii as follows:

¹²³ C. E. Dutton: Hawaiian volcanoes. Fourth Ann. Rept. U. S. Geol. Survey, 1884, p. 96.

"The superficial crust of cooled lava undergoes rupture at numberless points and little rivulets of lava are shot out under pressure. Preserving their liquidity for a short time they spread out very thin and are very quickly cooled, forming pahoehoe. Scarcely is one of these little offshoots of lava cooled when it is overflowed by another and similar one, and this process is repeated over and over again. In a word, pahoehoe is formed by small offshoots of very hot and highly liquid lava from the main stream driven out laterally or in advance of it in a succession of small belches. These spread out very thin, cool quickly, and attain a stable form before they are covered by succeeding belches of the same sort."

Green¹²⁴ has written of the Hawaiian pahoehoe as follows:

"This class of lava we saw flowing from the aa stream of 1859, showing that it is not a different kind of lava, but merely a different form taken under different circumstances of flowing. The lava seems to form pahoehoe when it is not in too great quantity and runs out quietly. For instance, the stream that broke out from the aa stream of 1859, while we were watching it, seemed first to form into a flattened spheroidal mass, the crust of which was constantly cooling and the fresh supply of molten lava was constantly increasing its size. At last a limit seemed to be arrived at between the retaining power of the cooling crust and the pressure of the column of liquid lava inside it, when the molten lava would break away from the lower edge of the dome and form another just like it and close to it, and so on, the molten lava from the aa stream continually keeping up the supply and running from one to another, forming a succession of domes, most of which were hollow and in many the top has disappeared. . . . The domes we look upon, as explained above, as hydrostatic effects on a cooling spheroidal mass of lava."

Dana¹²⁵ observed that pahoehoe shows "by the fine and coarse flow lines over it that it cooled as it flowed . . . often wrinkled, twisted, ropy, billowy, hummocky, knobbed, and often much fractured." In places it was found to have a glassy crust one-half an inch or less in thickness.

From the study of the well preserved lava surfaces on the Snake River plains of Idaho, Russell¹²⁶ described the origin of pahoehoe as follows:

"The origin of the peculiar and highly characteristic pahoehoe surface is due to the flow of viscous lava, which in consistency resembled asphaltum or pitch. The onward motion was not a continuous flow, as in the case of thoroughly liquid substance, but the surface and front of the advancing stream stiffened and bulged upward, and the more thoroughly molten material within broke through the tenacious but still plastic surface portion and advanced as a well-defined stream for perhaps a few yards or rods, and in turn stiffened at the surface and expanded on account of pressure from within and halted

¹²⁴ W. L. Green: *Vestiges of the Molten Globe*, pt. ii; *The Earth's Surface Features and Volcanic Phenomena*. Honolulu, 1887, pp. 172, 173.

¹²⁵ J. D. Dana: *Characteristics of Volcanoes*. New York, 1890, p. 9.

¹²⁶ I. C. Russell: *Geology and water resources of the Snake River plains of Idaho*, Bull. U. S. Geol. Survey, No. 199, 1902, p. 91.

with a curved front bulging outward. These slow-moving, viscous streams crossed one another, but became more or less thoroughly intermingled. This manner of progression, accompanied by many variations in detail, can be plainly seen on the congealed surfaces now remaining, especially near the sources of the lava stream."

Hitchcock¹²⁷ ascribed the hummocky character of the common pahoehoe of Hawaii to the fact that the lava stiffens very quickly after exposure. An illustration (plate 51) from the flow of 1880-1881, near Hilo, shows typical pillow forms in the right side of the view.

"Standing by this variety of lava as it forms, one sees that it is a stream of liquid material, and if a stick be thrust into it red lava will flow out. . . . The crust is flexible and is modulated by the motion of the liquid beneath."

In these explanations of the formation of pahoehoe there is some apparent contradiction. Thus Dutton, Green, and Hitchcock emphasize the smooth liquid flow or the quickly formed restraining crust, while Russell distinctly speaks of slow-moving viscous streams. A careful reading of the full descriptions by these authors, however, will show that while there is some contradiction of terms used in particular statements there is substantial agreement as to the mode of formation of pahoehoe and the characteristics of the lava that gives rise to it. The process is that of short, quick forward impulses of lava so liquid that it spreads rapidly in smooth-surfaced flows which, in turn, are quickly checked by the rapid formation of a tough viscous membrane on the exposed surface. This stretches under the pressure of the liquid interior until it stiffens and finally breaks, and the process is repeated over and over as the flow advances. The result is a smooth surface interrupted at shorter or longer intervals by rolls, swells, and domes.

FORMATION OF AA LAVA

Dutton¹²⁸ explains the formation of aa lava as follows:

"The fields of aa are formed by the flowing of large masses of lava while in a condition approaching that of solidification. Ordinarily they are very thick and cover a very large area, representing therefore an enormous mass comparable to that of a glacier. The movement is in some respects glacier-like, but with this difference; instead of having a sensibly constant temperature throughout, it is hot within and more or less viscous and nearly cooled on the surface. . . . During this slow glacier-like motion crushing strains of great intensity are set up throughout the entire mass, and its behavior

¹²⁷ C. H. Hitchcock: Hawaii and its Volcanoes. Honolulu, 1909, p. 280.

¹²⁸ Loc. cit., p. 96.

conforms strictly to that of viscous bodies. The superficial portions in part yield plastically to the strains, in part yield by crushing, splintering, and fissuring. The result is a chaos of angular fragments. The aa streams are always thicker than the pahoehoe and rise from 50 to 80 feet above them, being bounded by a margin of low cliffs and talus. . . . The same lava stream may exhibit pahoehoe or aa, according to the circumstances attending the flow, and the final form which the stream takes is quite independent of the chemical constitution of the lava."

Dana¹²⁹ described the rugged aa lavas of Kilauea as looking "like ploughed-up lava streams on a majestic scale" and, as far as visible, consisting of detached masses of very irregular shapes and confusedly piled up to nearly a common level. In some of the aa streams there are occasional bomb-like masses, in striking contrast with the typical aa, smoothish on the outside and more or less rounded and boulder-like, and ranging from a few inches to 10 feet or more in diameter. Some of these have a laminated structure of alternating concentric layers of hard, slightly vesicular lava, with softer scoriaceous material. Some with a hard outside shell seemed to be filled inside with fragments of reddish or grayish scoria. Common sizes are 3 to 5 feet in diameter, and they lie in the midst of the blocks of aa, "proving that all had a common origin," and that the rounded masses are not true bombs. Dana also observed that the same stream may change from pahoehoe to aa and back again in different parts of its course, and he ascribed the origin of aa lavas to the presence of ground moisture, the ascending vapors of which chill the flow and cause it to break up.¹³⁰ He characterizes the typical aa as

"roughly cavernous, horridly jagged, with projections often a foot or more long that are bristled all over with points and angles. . . . The reader's conception of it will be feeble at best if he has not already had a view of chaos."

Russell¹³¹ accounted for the formation of aa as follows:

"On the rate of flow, or, more definitely, on the ratio of rate of flow to rate of surface cooling, depend certain marked contrasts in the resultant surface features. When motion was slow and continued after the lava had become viscous, the stiffened crust was left with either a generally smooth, flat surface, or acquired oval stream-like ridges, bulging mounds and dome-like swells, while the crust formed where motion was more rapid or had continued after the surface had passed to a rigid condition became broken and the blocks were variously displaced and heaped up so as to produce excessive roughness."

¹²⁹ J. D. Dana: History of changes in Kilauea. *Am. Jour. Sci.* (3), vol. xxxiv, 1887, pp. 362-364.

¹³⁰ J. D. Dana: Characteristics of Volcanoes. New York, 1890, pp. 241-245.

¹³¹ J. C. Russell; *Bull. U. S. Geol. Survey*, No. 199, 1902, p. 90.

Hitchcock¹³² said of the Hawaiian aa: "The roughness of it beggars any possible description." Sheets of it, somewhat compressed and modified, can be recognized among the older beds, but "they must not be confounded with the spherical or rounded masses analogous to the columnar structure." He concluded that the study of aa lava has not revealed its nature and origin.

Day and Shepard¹³³ attribute the formation of aa lava to the rapid expansion of escaping gases and the consequent cooling.

"Great blocks appear to have cooled in this way so rapidly that no opportunity was given for the suddenly projected and rapidly expanding lava outbursts to 'heal' and resume liquid flow. The projected masses are cooled almost instantly throughout their mass and remain discrete blocks of the roughest and most ragged outline, which are pushed forward thereafter in a manner which has been likened to a 'moving stone wall,' beneath which the advancing liquid can rarely be seen. This hypothesis of the manner of formation of aa lava has encountered no limitation from a field examination of aa flows at the point of outbreak, and enjoys still further confidence from the fact that this is almost the only conceivable method of bringing about a nearly instant cooling throughout the mass of a very large block of lava. (Aa blocks are sometimes reported to reach the size of a small house.) Any manner of cooling from the outside inward in such masses must have resulted in much mechanical deformation during the forward movement after the surface had 'set,' causing rupture and outbursts of imprisoned liquid, none of which were found in the field."

The total lack of agreement as to the cause of aa lava is obvious. Among the authors quoted—Dutton: large viscous flow; Dana: influence of ground water; Russell: rapid flow of stiff lava; and Day and Shepard: cooling effect of escaping gases—there is apparently a wide range of hypothesis; but they naturally fall into two groups: (1) those that depend on the brittleness of highly viscous lavas, and (2) those that invoke the chilling effect of volatile substances. Day and Shepard's criticism of the first group would seem to be valid at least in regard to the coarser varieties of aa. To a certain extent the theoretical differences may be due to disagreement as to the facts in the field. Thus Dutton and Dana state that the same flow may change from aa to pahoehoe and back again in different parts of its course, while Russell finds that aa is particularly characteristic of the middle and lower portions of flows which exhibit typical pahoehoe in the upper parts of their courses.

¹³² C. H. Hitchcock: Loc. cit., pp. 281, 283.

¹³³ A. L. Day and E. S. Shepard: Water and volcanic activity. Bull. Geol. Soc. Am., vol. 24, 1913, p. 599.

DEVELOPMENT OF SPHEROIDAL AND PILLOW-LIKE FORMS

Green¹³⁴ observed the development of domical surface forms on pahoe-hoe, as described in a previous quotation, and adds:

"The domes we look upon . . . as hydrostatic effects on a cooling spheroidal mass of lava. In the first place the lava tends to form great flattened spheroids, not so much because it is all viscous like porridge, which tends to pour in spheroidal masses, but because the instant it is exposed to radiation a tough skin or pellicle forms on the surface and holds the molten lava inside, whilst the constant new supply expands the whole equally in every direction."

The great flow of 1859 reached from near the top of Mauna Loa on the north side to the sea, a distance of 38 miles. After it had flowed into the sea continuously for six months, Green writes:¹³⁵

"The red-hot molten lava was quietly tumbling into the sea over a ledge perhaps 6 to 8 feet high and 500 to 600 feet long. The lava did not seem to be quite so liquid or of such a bright color as it did when it ran out of the openings in the side wall of the aa stream up in the mountains some months before. It ran more like porridge in great flattened spheroids, which were sometimes partially united together and sometimes almost separate. . . . It was not until after each spheroidal mass had disappeared for a second or two under the water that puffs of steam came to the surface."

It is suggested that the tendency to form spheroids in the molten state may be in part the origin of basaltic columns, which under compression, cooling, and contraction, while still semifluid, tend to take on a six-sided columnar form. The same principle is thought to account for spheroidal weathering in lavas.

Anderson¹³⁶ saw secondary cones composed of masses like pillow lava, evidently of subaerial construction, on the surface of a recent flow in Iceland, where it occupied a river valley.

Flett¹³⁷ compared the light spongy lava pillows of Port Isaac, Cornwall, with the bombs projected off Pantelleria in 1891, which rolled on the surface of the water in clouds of steam and finally exploded with a loud noise. Presumably any such that sank without exploding formed light cavernous pillows.

In 1910 Dr. Tempest Anderson¹³⁸ described his observations on pillow-like forms in process of formation at the volcano of Matavanu, in Savaii,

¹³⁴ W. L. Green: Loc. cit., pp. 172, 173.

¹³⁵ W. L. Green: Loc. cit., p. 277.

¹³⁶ Tempest Anderson: Quar. Jour. Geol. Soc. London, vol. 64, 1908, p. 271.

¹³⁷ J. S. Flett: Quar. Jour. Geol. Soc. London, vol. 64, 1908, p. 270.

¹³⁸ Tempest Anderson: The volcano of Matavanu, in Savaii. Quar. Jour. Geol. Soc. London, vol. 66, 1910, pp. 621-639.

Samoa Islands (plate 23, figure 2). Where a vigorous flow of lava was entering the sea explosions were almost continuous, and the place was obscured by clouds of steam, from which fragments of red-hot lava and showers of black sand were projected.

"Where the lava was flowing in smaller quantity explosions were much less noticeable and the lava extended itself into buds or lobes. The process was as follows: an ovoid mass of lava still in communication with its source of supply and having its surfaces, though still red-hot, reduced to a pasty condition by cooling, would be seen to swell or crack into a sort of bud with a narrow neck like a prickly pear on a cactus, and this would rapidly increase in heat, mobility, and size till it either became a lobe as large as a sack or pillow, like the others, or perhaps stopped short at the size of an Indian club or large Florence flask. Sometimes the neck supplying a new lobe would be several feet long and as thick as a man's arm before it expanded into a full-sized lobe; more commonly it would be shorter, so that the freshly formed lobes would be heaped together. They looked white-hot, even in daylight, and as the waves washed over them the water seemed to fall off unaltered without boiling, owing probably to its being in the spheroidal condition."

Plate 23, figure 2, which is a copy of Anderson's plate lii, is a view from the lagoon near Seleaula. The lava in the background has cooled slowly and assumed the usual corded structure. In the foreground many of the lobes have flowed into the water and been chilled before they had time to do this.¹³⁹

Dr. Arthur L. Day, Director of the Geophysical Laboratory, has kindly permitted me to use the accompanying photographs (plates 22 and 23) of newly formed pillows at the crater of Kilauea. Dr. Day writes in explanation: "The print which shows us collecting gases (plate 22, figure 1) was made within a few feet of the liquid lava lake, and the pillows which it contains formed in plain view three days before the picture was taken. The manner of formation, I think, is precisely described in the manuscript which you showed me some time ago." The reference here is to brief manuscript notes that were used in presenting an outline of this paper before the Society on December 30, 1913, embodying in outline the theory of the pillows that is given somewhat more fully in the following paragraphs.

¹³⁹ See also *Geogr. Jour.*, vol. xxxix, 1912, pp. 123-132, and *Rept. Brit. Asso. Adv. Sci.*, Sheffield meeting, 1910, p. 654.

A THEORY OF BULBOUS BUDDING

GENERAL DISCUSSION

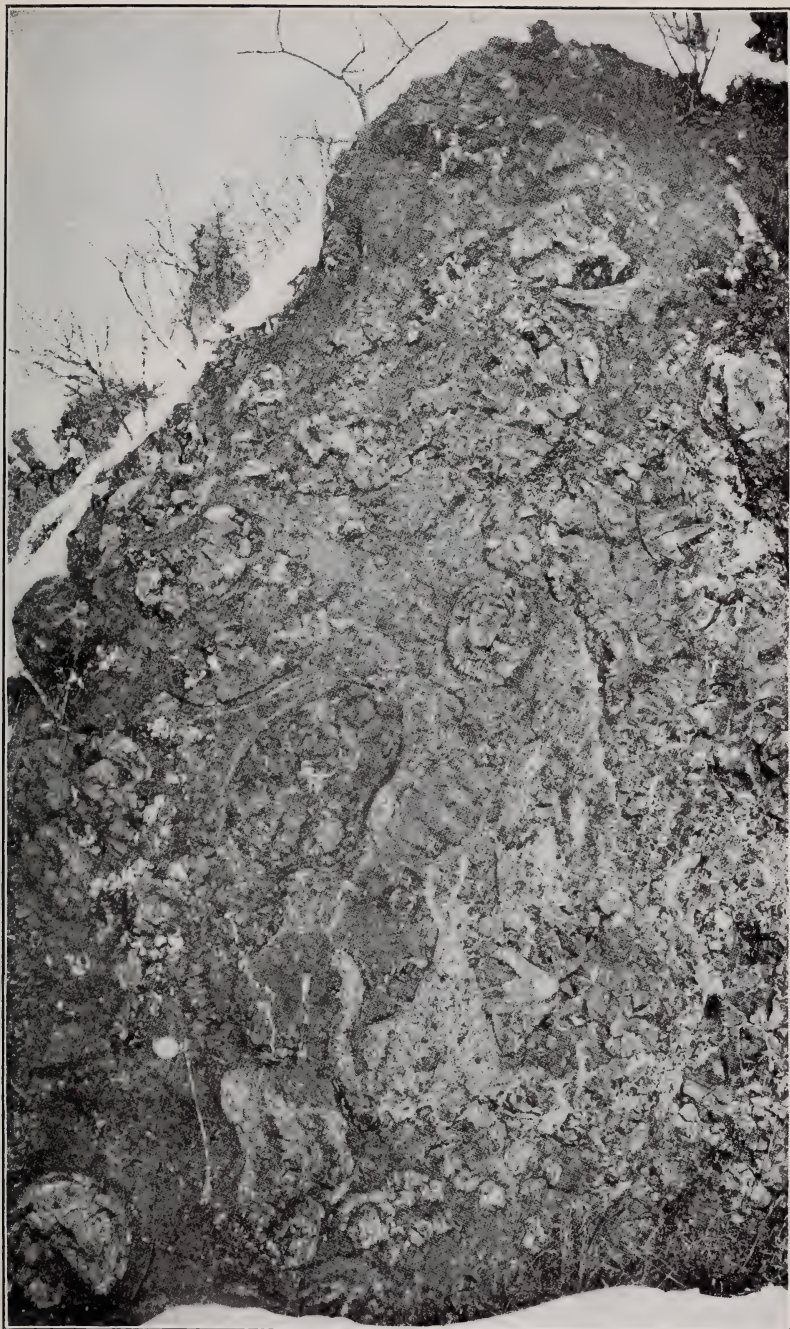
A comparison of the descriptions and illustrations of pillow lavas from various parts of the world with the excellent examples in the Watchung Mountain basalts in New Jersey shows that in all essential characters they are identical. With the advantage of the numerous studies and discussions of origin that have been published, and especially the illuminating direct observations of Green, Anderson, and Day, it should now be possible to devise a satisfactory theory to account for the production of these forms without resort to strained or improbable assumptions. This I have attempted to do in the following paragraphs.

1. HIGHLY LIQUID LAVA

Since pillow structure is found only in free-flowing basalts and closely related lavas, it is evident that any high degree of viscosity must serve effectually to prevent its formation. Hence it becomes necessary to reject such characterizations as "highly viscous pahoehoe," which some authors (including myself) have used in former years to describe this structure. On the contrary, the necessary physical condition of the lava is rather its capacity for retaining a high degree of liquidity through a relatively long period of cooling and the development of a notable degree of viscosity only within a limited range of temperature as it approaches rigidity.

2. SMALL CONTINUOUS SUPPLY

In the declining stages of a large flow, when the lava lies nearly motionless, the formation of small cracks and orifices in the cooling crust relieves the internal pressure, and hence checks still further the forward motion by permitting the escape of liquid lava at the front and along the sides of the flow or, in case of sufficient slope or internal pressure from any cause, even on its upper surface. Thus the process may substitute a multitude of small flows for the one great flow that has become retarded or stopped in its course, or in the case of slow gentle extravasation of lava from the beginning the multiple-flow principle may come into play at once. In either case the continuation of the process depends on the maintenance of favorable conditions. Thus it may be terminated, for example, by the failure of the supply of lava or the increase of the supply to the point where large flows would be inaugurated (or reestab-



BOULDER OF PILLOW BASALT

This boulder lies at the foot of the cliff below the quarry and observation tower, east of Greenfield, Massachusetts. The interstitial matter is a mixture of sand and glass (tachylite), much of which shows flow structure. To the right of the watch and chain and extending upward twice the length of the chain a series of four rounded masses are connected by narrow necks and send out small lobes. "The effect of the pile of great round blocks, with comparatively small amount of interstitial matter, can only partly be given by the photograph" (Emerson). Reprinted by permission of Prof. B. K. Emerson from Bulletin of the Geological Society of America, volume 8, 1897, plate 5.

lished) or by a notable rise in the temperature of the supply, as will appear in the following sections.

3. BULBOUS BUDDING

With suitable temperature the numerous small flows will form bulbous or elongated masses. On exposure to the air a tough membrane quickly forms on the surface of each little outburst, and the pressure of the lava within expands each bulb by stretching the skin until stopped by its increasing rigidity. The stretching produces in the thickening and stiffening crust a pseudo-flow structure parallel to the outer surface by the stretching and flattening of vesicles and the tangential arrangement of microlites and other individualized or segregated constituents of the magma.

On final stiffening of the crust, with continued pressure of the liquid contents within, cracking occurs and the process of budding is repeated, and so on indefinitely as long as the supply of lava continues in suitable amount and at favorable temperatures, the liquid flowing through a succession of pillows connected by short necks or necks of no appreciable length at all. Some of these channels may become enlarged by the solvent action of the magma if the temperature of the supply is sufficient, or all of them may be closed by freezing as the flow through them diminishes or the temperature falls. This latter event may be postponed by layers of pillows of succeeding generations that form on the first, each layer protecting the pillows beneath from rapid cooling and prolonging the period during which lava may continue to pass through them and increase the extent of the flow.

Thus the process, as I have conceived it, resembles very closely that of pahoehoe, but *not* "viscous pahoehoe," which does not seem to exist except as to a relatively thin crust on a fluid lava. In this budding process the individual pulsations are smaller and a restraining crust forms more quickly, thus preventing the tendency to broad, flattened forms that characterizes typical pahoehoe. Probably also the temperature of the lava is somewhat lower in most cases, and this would further hasten the production of the viscous film, on the prompt development of which the structure depends. Hence with varying conditions all degrees of transition would occur between typical pillow structure and pahoehoe, either passing into the other or alternating with it, according to circumstances.

4. SEMI-MOLDED, IMMOBILE FORMS

As these masses are formed, first on the ground or the floor of a lake or sea and then in more or less rapidly succeeding generations one on

another, they tend to assume somewhat rounded or domed upper surfaces and molded bases. Hence the pillows at the bottom of a flow are apt to be flat beneath, unless a soft silt or ooze permitted some degree of sinking into the sediment and the development of curved lower as well as upper surfaces. Those higher in the bed tend to fit more or less perfectly on the underlying ones, the degree of adaptation varying inversely with the promptness with which a restraining integument is developed. It is particularly to be noted that according to this view the pillows immediately assume fixed positions as they are formed. There is no rolling over and over on one another, as so many have supposed, nor interspheroidal motion of any kind involved in their production; neither are the pillows pressed together while still plastic, since only those in process of formation at the surface are soft and yielding.

From the mode of construction it necessarily follows that the various axes of the masses under the influence of gravitation assume positions approximately parallel to each other, the longest marking the direction of flow and the shortest the vertical at the time of their formation (see plate 19, figure 1, and plate 23, figure 1). Other conditions being equal, the steeper the slope the more elongated and bolster-like will be the pillows. An increased pressure and excessive flow of lava would enlarge the bulbs so rapidly that they would flatten out and tend to merge into the sheet-like pulsations which Dutton has described as characteristic of pahoehoe. A similar result would follow on a considerable increase in temperature, since this would delay the formation of the tough capsule on which the rounded shapes depend. As pointed out by Capps, the upper surface of a bed of pillows consists of "a succession of domes resembling the surface of a magnified cobblestone pavement."¹⁴⁰

Several observers have noted the general parallelism of the longest axes of the pillows, and the further fact that they are approximately parallel to the bedding-planes of accompanying sedimentary rocks, but no effort has been made to interpret these relations. Under any supposition of rolling, whether in a surface flow or by the action of intense dynamic forces beneath the surface, the longest diameters would necessarily mark the direction at right angles to that of the movement. Capps has emphasized the value of the sharp distinction between the top and bottom surfaces of a sheet of pillow lava in the interpretation of a complicated structure, but it is possible for these distinguishing characters to be greatly modified, and they may even disappear altogether. For

¹⁴⁰ S. R. Capps: Manuscript report on the Ellamar district, Alaska, U. S. Geol. Survey, to which I am permitted to refer in advance of publication.

instance, as already noted, pillows formed on yielding mud or ooze will sink into their bed and develop rounded outlines beneath that may be indistinguishable from the upper surface. Furthermore, pillows may constitute any portion of a flow that is otherwise massive, and hence massive lava may replace the ordinarily flat-bottomed pillows of the base or the multidomical upper surface or both.

5. SEPARATION OF INDIVIDUAL PILLOWS

Each budding extrusion is a separate diminutive lava flow, and within narrowly restricted limits subject to the same "accidents" as larger flows, such as overlapping and interfering with one another. However, at the time of their formation they are connected in irregular zigzag series, and in some of the older flows numerous such connections are well preserved, and many examples of pillows connected by necks to massive lava have also been described (compare plate 18, figure 2, and plate 19, figure 1, with plates 22 and 23). The slight connection of the pillows with each other and with the parent mass is a point of weakness, however, that may readily be severed by contraction while cooling or by slight subsequent warping or other movement, leaving the individuals wholly isolated.

The falling away of pendulous ellipsoidal masses as the lava slowly drops over a cliff, as observed by Green in Hawaii, may also produce separate individuals if their outer crusts become sufficiently hardened to prevent the welding of the masses together. This condition would probably obtain wherever the masses fall into water, although under favorable conditions of temperature and rate of flow the presence of water would not be necessary.

6. INTERSPHEROIDAL CAVITIES AND BRECCIA

The spalling off of glass fragments, which may be expected to occur in most cases—perhaps most actively in the water—partially fills the interspheroidal spaces with breccia, where such openings persist, owing to the failure of the pillows to fit together perfectly. These spaces may also contain fine sediment where the lava has flowed into soft mud or ooze under water, or sediment of any kind may be subsequently washed into the interstices from above, whether the flow is subaqueous or sub-aerial. Occasionally a growing pillow may crack during its expansion in such a manner as to spill a portion of its liquid contents into the spaces between underlying or adjacent pillows. Thus, for example, in some of the Carboniferous pillow basalts of Fife and Kinross, Scotland, lava similar to that of the pillows has filled a part of the openings.

Geikie suggests that portions of the lava that were the last to solidify were "forced into the crevices between the already solid pillows."¹⁴¹

Where conditions suitable to their production exist, the spaces still remaining unfilled offer favorable places for the wonderful variety of beautifully crystallized minerals for which some of the localities are noted. These include quartz, calcite, the zeolites, datolite, prehnite, pectolite, epidote, and many other less abundant species. Secondary processes, especially in lavas that become deeply buried, have transformed the glassy crusts and interstitial fragments in many flows into green chloritic mixtures, and in many regions corresponding changes have taken place within the crystalline lava as well. These processes are well illustrated by the spilites and the greenstones.

7. RADIAL JOINTING

Columnar jointing, when developed in pillow lavas, naturally forms at right angles to the cooling surfaces, as in other columnar lavas; hence the radial arrangement so commonly seen in the spheroidal, ellipsoidal, and pillow-like masses. In many examples this structure is developed in great perfection, and in some localities it is emphasized by the deposition of calcite in the joint cracks, but as a rule it is most distinctly seen in weathered sections. A shell-like concentric parting is found in some pillow lavas, with a strongly developed zonal structure, and it is characteristic of the tachylite crusts generally to scale off easily and break into fragments.

8. DEGREE OF VESICULARITY

The individual masses become more or less vesicular according as much or little gas is retained in solution by the liquid lava. In many examples the outer crust is entirely free from vesicles, and concentric layers or scattering lines of cavities or amygdules appear only in the crystalline mass within, the most scoriaceous parts of all occurring in the central portions of the pillows. This would be the normal result where the liquid remains in equilibrium, holding its volatile constituents until they are released by the process of crystallization. Glass, being a supercooled liquid that has become rigid without crystallization, often retains its volatile matter in solution, and in such case does not become notably vesicular. Where there is supersaturation of volatile constituents their rapid escape makes the whole mass spongy with vesicles, and their continued separation from the liquid interior in advance of crystalliza-

¹⁴¹ A. Geikie: *The geology of central and western Fife and Kinross*. Mem. Geol. Survey of Great Britain. Scotland, 1900, p. 72.

tion causes the accumulation of vesicles in greater numbers near the upper surfaces of the pillows—a condition that has been recorded by several observers.

Barrow¹⁴² has compared vesicular and amygdaloidal pillows to the slag blocks that were used in the construction of the great Tees Breakwater. The slag flowed like water and gave off no gas as it was run into the box-shaped trucks in which it was molded; but when broken by the waves these blocks were found to be very vesicular, especially at the center, and the vesicles were arranged roughly parallel to the outer surfaces. It was concluded that the gases were held in solution and finally released only on the crystallization of the interior.

9. HOLLOW PILLOWS

Should the flow of the interior liquid fail from any cause, such as the freezing of an intervening passage or the opening of freer channels in another direction, a growing pillow may be drained on cracking and thus become wholly or partially hollow. However, most hollow pillows seem to owe their cavernous condition to either an excessive amount of contained gases, giving rise to a central steam cavity of large size, or to the breaking down of a spongy core by weathering. This latter process may even precede the breaking away of the outer shell.

10. EXTENT OF FLOW

The budding of the front and lateral margins of a nearly stagnant flow and the successive budding of these spheroidal masses to form similar ones, after the manner of some species of bulbous cactus, may lead eventually to the covering of a considerable area, the extent finally attained depending chiefly on the length of time during which a moderate supply of sufficiently liquid lava continues. On flats and gentle slopes the lateral extent of a small flow of this nature will necessarily be small; but with a long-continued supply of lava the formation of successive layers of pillows, one on another, will gradually build up a slope like an aggrading river, and with increasing gradient the range of flow will be increased. Thus both the depth and lateral extent of a pillow lava are contingent on the length of time during which a suitable supply is maintained.

The relative amounts of spheroidal and massive lava in any flow will depend on many physical conditions, among which the composition of the lava, the rate of extrusion, the initial temperature, and the temperature range within which the lava remains a mobile liquid are probably of

¹⁴² G. Barrow: Quar. Jour. Geol. Soc. London, vol. 64, 1908, p. 271.

prime importance. The mobility hinges on both the composition and the temperature and will be greatly affected by the kinds and proportions of both the mineral-forming and the volatile constituents.

11. CONTACT WITH WATER

The influence of water on a subaqueous flow or one entering a lake or sea can not yet be specified with any considerable degree of confidence. Possibly characteristic differences between subaqueous and subaerial flows exist, but the principal features developed under the two conditions are indistinguishable in the present state of knowledge. Presumably the rate of cooling is somewhat accelerated by immediate contact with water, at least in certain stages of the process, as at the initial budding of each new bulb or pillow, and this probably has a modifying influence on the size, shape, and other characters of the completed individuals; but to a great extent these must depend also on the initial temperature of the lava of each diminutive outbreak, the pressure under which it flows, its chemical constitution, and other indeterminate factors.

Contact with water may also have the effect of either hindering or promoting the formation of the pillow structure itself. Conditions of temperature and flow that are favorable to the production of extensive pillow lava on land, for example, may become so modified by flow into water that the extent of the structure will be much restricted. On the other hand, it is conceivable that a flow of such volume and fluidity as would spread rapidly into a continuous sheet on land might be checked and largely transformed into pillow lava on entering a body of water. Hence it seems safe to conclude that neither the presence nor the absence of water, *per se*, can be predicated as particularly favorable to the formation of this structure.

12. INTRUSIVE PILLOW LAVA

Direct intrusion of lava into soft oozes or loose sediments on the sea-bottom in general would differ from subaqueous eruption only in the slight resistance to flow offered by the sediments and in less rapid cooling, perhaps, owing to the absence of convection currents. In other respects such an injection would be essentially an extrusive flow. Indeed, a subaqueous eruption on a sea or lake bottom of such insubstantial character would of necessity penetrate the underlying sediment in part, and likewise a lava stream from the land would sink into a semiliquid ooze or quicksand on entering a body of water where such conditions prevail. While, strictly speaking, either of the foregoing types must be called intrusive, the controlling condition is manifestly the same in both, namely,

the incompetence of the strata to sustain the weight of a flow. To apply the term intrusive to the case of a land lava entering water, however, leads to the rather grotesque conception of a surface flow again penetrating the earth and becoming intrusive after having traversed the surface of the land, perhaps for many miles!

Platania¹⁴³ thinks the globular basalt of Acireale, with its mud-filled interstices, "probably due to the injection of magma into a thick stratum of submarine silt." Lawson¹⁴⁴ considers the San Francisco pillow basalt intrusive in the accompanying sediments, although Ransome¹⁴⁵ had formerly interpreted it as a surface flow on Point Bonita (plate 18, figure 1) and intrusive on Angel Island. Several examples of the structure in Great Britain have been regarded by some authors as probably due to the invasion of soft sediments in process of accumulation by an igneous magma, and Reuning¹⁴⁶ thinks the splendid Hessian occurrences, where many of the pillows still hang together by narrow necks and in which large masses of sediment are inclosed in places, may have sunk into the silty ooze of the sea-bottom.

Platania refers to an experiment by Johnston-Lavis in which a dense viscous liquid on being injected into another assumed spheroidal forms with slight necks connecting them, some of which were severed, leaving the globes detached. Whether this would occur in the conditions under consideration would depend largely, perhaps, on relative density. A very light, insubstantial ooze would probably offer too little resistance to cause the separation of a lava that had not already begun the budding process. On the other hand, it would not interfere with the development and the extension of this process through its mass, and this would give rise to pillow structure in every respect like that which forms on the land or the firm sea-bed, except perhaps in the absence of flat-bottomed pillows at the base of the flow.

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¹⁴³ G. Platania: Geological notes of Acireale. The South Italian Volcanoes, ed. by H. J. Johnston-Lavis. Naples, 1891, pp. 37-44.

¹⁴⁴ A. C. Lawson: San Francisco Folio, U. S. Geol. Survey.

¹⁴⁵ F. L. Ransome: The eruptive rocks of Point Bonita. Bull. Dept. Geol., Univ. of Cal., vol. i, 1893, pp. 71-113; The geology of Angel Island. Ibid., vol. i, pp. 193-234.

¹⁴⁶ Ernst Reuning: Diabasgesteine an der Westerwaldbahn Herborn-Dreidorf. Neues Jahrb. Min., etc., B. B., vol. xxiv, 1907, pp. 390-459.

George Otis Smith, Director of the United States Geological Survey, for valuable assistance from the Survey library and for access to the proof-sheets and manuscripts of unpublished reports; to Dr. Henry B. Kümmel, State Geologist of New Jersey, for permission to use the materials and results of investigations that have been made for the State Survey; to Prof. William H. Hobbs, of the University of Michigan, and to Dr. F. L. Ransome, of the United States Geological Survey, for the loan of photographs and for assistance in the search for literature; to Prof. B. K. Emerson, of Amherst College, for the use of one of his illustrations. I have also had important assistance in locating the literature of the subject from Mr. Bernard Hobson, F. G. S., of Sheffield, England.



SPHEROIDAL WEATHERING OF BASALT

Showing concentric exfoliation. Smalley's Quarry, North Plainfield, New Jersey. Photograph by Mr. Charles Quint, furnished by Mr. John A. Manley

MECHANICAL COMPOSITION OF CLASTIC SEDIMENTS¹

BY JOHAN AUGUST UDDEN

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CONTENTS

	Page
Introductory.....	656
Methods of analysis.....	657
Materials examined.....	659
The three classes of sediments.....	659
Glacial till.....	659
Water deposits.....	661
General discussion.....	661
Sediments in glacial waters.....	661
Materials from single layers of deposits in glacial waters.....	662
Terrace materials.....	662
Materials from single layers in terrace sands.....	663
Silts in terraces of the Mississippi.....	663
Sediments in present streams.....	664
Sediments in small streams.....	664
Drifted sediments in large streams.....	665
Silt from large streams.....	666
Lake deposits.....	667
Deposits in the sea.....	667
Classification.....	667
Beach gravel.....	668
Silts in harbors.....	668
Deposits on the continental shelf in the West Atlantic.....	669
Sediments on the submerged west slope of the west coast of America.....	672
Deposits in the Bering Sea.....	673
Deposits in the sea near volcanoes.....	674
Deposits near the margins of ocean basins.....	675
Wind deposits.....	676
Classification.....	676
Lag gravels.....	676
Coarse drifting sand.....	677
Dune sand.....	678

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	Page
Incipiently blown sand.....	682
Lee sand.....	682
Dust.....	683
General discussion.....	683
Miscellaneous collections of dust.....	683
Dust collected by apparatus from the atmosphere.....	686
Dust taken on surfaces above the ground.....	688
Shower dust.....	689
Tables of mechanical analyses.....	692
Till (Table 1).....	692
Water deposits (Tables 2 to 20).....	693
Wind deposits (Tables 21 to 29).....	713
Sands containing magnetite (Table 30).....	727
Loess (Table 31).....	728
"Gumbo" (Table 32).....	729
General discussion of data.....	730
Modes of sedimentary sorting.....	730
Law of the chief ingredient.....	732
Law of decreasing admixtures.....	733
Law of the sorting index.....	735
Law of the secondary maximum.....	736
Differences in sediments due to different modes of work.....	738
Washed sediments.....	738
Drift and blown material, silt, and dust.....	738
Differences between water and wind sediments.....	740
General discussion.....	740
Difference in grade distribution.....	740
Difference in coarseness of the chief ingredient.....	741
Difference in the quantity of the chief ingredient.....	742
Difference as to average number of grades.....	742
Difference in uniformity of composition.....	743
Restrictions in the application of some characteristics.....	743

INTRODUCTORY

In an earlier paper² I have published mechanical analyses of a number of samples of wind sediments and have described the conditions under which these samples were formed, classifying them into lag gravels, drifting sand, lee sand, and atmospheric dust. It was my purpose to present some reliable measurements on the mechanical composition of such deposits. It was evident from that study that wind sediments are less heterogeneous in their mechanical make-up than water sediments are. This fact is quite generally recognized. It is readily

² The Mechanical Composition of Wind Deposits. Augustana Library Publications, Number 1, Rock Island, Illinois, 1898.

inferred from consideration of the physical forces and conditions involved. The lightness of the air prevents it from moving pebbles more than about one centimeter in diameter, except on occasions so rare that wind deposits of that coarseness are practically non-existent. Likewise, dust grains measuring less than one sixty-fourth millimeter in diameter are so easily held in the atmosphere that they are readily scattered everywhere over the earth's surface and are too widely dispersed to accumulate anywhere as the main ingredient in a distinct deposit, unless it be in some permanently quiet part of the sea.

For the purpose of obtaining similar measurements on the size of the clastic elements present in other sediments, I later made collections of aqueous and glacial deposits and made similar analyses of these. It was my wish to extend these studies to include the widest possible range of sedimentary conditions; but lack of time for several years to pursue the subject and absence of prospects to follow the work any farther have caused me to decide to publish the data now in hand, however incomplete. I shall make only a brief discussion of their significance.

METHODS OF ANALYSIS

In making the analyses the clastic elements have been separated into groups of different coarseness. These groups I have called grades. Each grade consists of particles ranging in size between limits marked by two contiguous separations. These separations have been made in a uniformly decreasing series of diametrical dimensions, so as to give the largest bodies in each grade twice the diameter of the largest bodies in the next finer grade, throughout, from the coarsest to the finest. In general, when the finest grades have been found in quantities amounting to less than one-tenth of a per cent of the whole sample, they have been neglected or marked as a trace. For the sake of convenience, the following designations for different grades will be used in this paper:

	Diameters in millimeters.	
	From—	To—
Large boulders.....	256	128
Medium boulders.....	128	64
Small boulders.....	64	32
Very small boulders.....	32	16
Very coarse gravel.....	16	8
Coarse gravel.....	8	4
Gravel	4	2
Fine gravel.....	2	1
Coarse sand.....	1	1/2
Medium sand.....	1/2	1/4

	Diameters in millimeters.	
	From—	To—
Fine sand.....	1/4	1/8
Very fine sand.....	1/8	1/16
Coarse silt or dust.....	1/16	1/32
Medium silt or dust.....	1/32	1/64
Fine silt or dust.....	1/64	1/128
Very fine silt or dust.....	1/128	1/256
Coarse clay.....	1/256	1/512
Medium clay.....	1/512	1/1024
Fine clay.....	1/1024	1/2048

In most samples which have been examined there is one medium grade, which is present in greater quantity than any other, while the other grades diminish in mass the more the size of their particles differ from the medium grade. The latter will here be called the *chief ingredient*, or the *maximum*, and the two decreasing series on either side will be referred to as the *coarse* and the *fine admixtures*. The ingredients in the grades nearest in size of its elements to the size of the elements in the maximum grade will be called the *proximate admixtures*, and these grades will be called the proximate grades. The grades most different in size of its elements from the size of the elements in the maximum ingredient will be called the *distant admixture*, and the same grades will be called the distant grades. In many samples the decrease in quantity of the admixtures away from the maximum is not continuous, but there is an increase in quantities from the proximate to the distant grades. In such case we may call one or more grades *secondary maxima*. It will also be convenient to refer to the grades of admixtures by numbers, designating them in pairs as the grades of the first, second, and third, etcetera, order from the maximum.

The separations of the materials measuring more than 16 millimeters in diameter were made by counting the pebbles and boulders of each grade and calculating the bulk or weight in each grade from the number of the pebbles or boulders, regarding them as perfect spheres of mean sizes in each grade; thus:

Sizes of boulders in millimeters.	Number of boulders.	Divisors used.	Percentages of grades to whole sample.
512-256.....	1	1	1.0
256-128.....	432	8	54.0
128- 64.....	2,624	64	41.0
64- 32.....	1,638	512	3.0

In practice it is necessary to first obtain a series of figures which give merely the relative magnitudes of the percentages sought, and from these the percentages are readily calculated. It has also been found that the best results are obtained not by counting the large number of boulders of the smaller sizes, as shown in the case illustrated above, but to find a chain of ratios between the whole mass of any number of boulders found in each two or three successive grades, and from these to calculate the relative magnitudes of the grades, thus:

Sizes of boulders in millimeters.	Ratios found by counting.	Relative magnitude of grades.	Percentages of grades to whole sample.
512-256	1	3.0	3.0
256-128	$\frac{142}{5}$	17.8	18.6
128-64	$\frac{175}{12}$	71.9	73.3
64-32	$\frac{7}{7}$	5.4	5.5
Total.....	.....	98.1	100.4

The grades having diameters from 16 to one-eighth millimeters have been separated by the use of sieves. The grades below this, consisting of very fine sand and all silt, dust, and clay, have been determined by microscopic measurements, by counts of the particles, and by deriving from these counts a chain of ratios in the same manner as in the case of the boulders and very coarse gravel. When more than one method has been used in the same analysis, the materials treated by different methods have been each separately weighed to determine the correct ratios of the sums of the grades belonging to each kind of material, differently treated.

In the microscopic work a one and one-half inch eye-piece and a one-sixth inch objective have been used throughout; likewise an ocular micrometer ruled in decimal squares.

MATERIALS EXAMINED

THE THREE CLASSES OF SEDIMENTS

The three principal kinds of mechanical sediments examined in these analyses are glacial till, aqueous deposits, and wind deposits.

GLACIAL TILL

Strictly speaking, glacial deposits are deposits left from melted ice without having been to the least extent sorted by the water resulting from the melting of the ice. This is the material known as till. Deposits formed by glacial streams or in ice-dammed lakes are really aque-

ous deposits, although they are often by writers classified as glacial, for the reason that they have structural features and a geographical distribution closely associating them with the till. Near places where glaciers have abraded the bedrock till no doubt exists, which consists of chiefly coarse material. It seems likely that till produced by mountain glaciers is coarser than till resulting from continental glaciation. All samples analyzed for this paper belong to the latter class. They are notably uniform in composition. Their clastic texture is evidently a result not of sorting, but of crushing. It is to be regarded as representing a certain stage in this crushing process for any particular sample. It would seem that the tills analyzed have been ground to nearly identical stages of fineness. The maximum ingredient is the same in five of the eight samples, consisting of fragments from one-sixteenth to one thirty-second millimeter in diameter. In one sample it is two grades coarser than this; in one, one grade coarser; and in one, two grades finer. The grades containing quantities which are measurable by this method of analysis number from 13 to 16 in different samples, and would no doubt have been a few more if the samples had been larger, for we know till contains large boulders ranging up to many feet in diameter; but it is safe to say that 99 per cent of the tills in Illinois and Iowa will not go much outside of 16 grades. If we average³ these samples, we find that the quantities are more than 1 per cent in 13 grades, from very coarse gravel to coarse clay, inclusive. Three more grades are represented by less than 1 per cent. The coarse admixtures exceed the fine admixtures considerably. In these samples there is 9 per cent more of coarse admixtures than of fine. This excess evidently represents a part of the till which is specially resistant to trituration in the ice.

List of Samples in Table 1

1. Yellow boulder-clay from six miles south of La Salle, Illinois.
2. Unweathered Kansan boulder-clay, Davenport, Iowa.
3. Blue boulder-clay, two miles north of Council Bluffs, Iowa.
4. Yellow boulder-clay from one-half mile east of Dimmick, Illinois.

³ In the discussion of this and all the following tables all averages referred to have been obtained by adding the percentages of all maxima, then the fine admixtures of first, second, and third, etcetera, order; likewise the coarse admixtures of the first, second, and third, etcetera, order, each separately, and then dividing the sums by the number of samples. In samples having more than one maximum, the highest one is taken as the chief ingredient and the others are treated as admixtures. In two or three samples, where two or three maxima are nearly of the same size, the selection of one to appear as the main ingredient has been arbitrary. For the tills a better way of averaging would perhaps be to average the middle grade, or the grade as near as possible equally distant from the extreme grades, and then average the other ingredients in successive order on either side.

5. Clay like the Kansan, section 2, Crescent township, Pottawattamie County, Iowa.
6. Yellow boulder-clay, Dimmick, Illinois.
7. Pinkish yellow boulder-clay on top of a yellow boulder-clay from a railroad cut one mile south of Oglesby, Illinois.
8. Boulder-clay, one-half mile east of Millsdale, Illinois.

WATER DEPOSITS

General discussion.—Deposits belonging to this class are many and various. A considerable number of analyses have been made, and while some important classes of sediments are not as well represented as they should be, it is believed that the data secured will give a general idea of the composition of most sediments excepting coarse beach material. They will be designated as sediments in glacial waters, terrace materials, sediments in small streams, sediments in large streams, and marine sediments.

Sediments in glacial waters.—The material examined was taken from deposits somewhat closely associated with till, and in situations indicating that the waters in which they were laid down drained glaciers. In some cases they were pockets in till, suggesting intraglacial water currents (number 10). In other cases they are from terraces produced in proximity to margins of glaciers (samples 9, 11, 12, 14, 16, 17, 18). Owing to the nearness of the unassorted glacial material, we expect to find deposits in such situations imperfectly sorted. The samples 9 to 18, inclusive, were taken across several layers of sand and gravel representing, as nearly as possible, uniform conditions of deposition. It will be seen that in these samples there are materials present in from seven to twelve different grades, averaging nine grades. Excepting one sample (15), the percentages exceed one in from five to nine grades. The maximum ingredient ranges from 20 per cent (sample 9) to 53.9 per cent (sample 14).

It will be noticed that the admixtures vary considerably, one extreme sample having only one grade of coarse admixtures (sample 15), while it has five grades of fine admixtures. In an average showing the general distribution of the quantities in all the grades in this class of sediments, this distribution appears decidedly askew, as the coarse admixtures, distant from three to four grades from the maximum, are present in much larger quantities than the corresponding fine admixtures. They produce a second maximum. This is a distinguishing feature of some other sediments and its significance will be discussed later. It must be considered a characteristic of poorly sorted material transported by drifting currents on the bottom under water currents and under winds.

List of Samples in Table 2

9. Glacial gravel in a terrace at Bureau, Illinois.
10. Gravel in the drift on the Government Island, Rock Island, Illinois.
11. Glacial gravel from near Peoria, Illinois.
12. Gravel from the glacial drift, Wyanet, Illinois.
13. Glacial gravel from near Hudson, South Dakota.
14. Glacial gravel from near Peoria, Illinois.
15. Glacial sand, Muscatine, Iowa.
16. Glacial sand from cross-bedded part of a bank, Wyanet, Illinois.
17. Glacial sand from a terrace, Bureau, Illinois.
18. Glacial gravel, Peoria, Illinois.

Materials from single layers of deposits in glacial waters.—Five samples were collected, each from a different single layer in glacial sand or gravel beds. These are as well sorted as some beach sands. Taken together with the other samples from glacial waters, which are poorly sorted, they prove that the currents of the glacial waters were unsteady, sometimes depositing coarse and sometimes fine materials. The coarse admixtures are greatly in excess of the fine admixtures.

List of Samples in Table 3

19. Glacial sand from a horizontal single layer, Wyanet, Illinois.
20. Glacial sand from a single layer in a cross-bedded bank, Wyanet, Illinois.
21. Glacial sand from an oblique single layer, Wyanet, Illinois.
22. Glacial sand from a horizontal single layer, Wyanet, Illinois.
23. Glacial sand from a single layer in a cross-bedded bank, Wyanet, Illinois.

Terrace materials.—Most terrace materials in Illinois and Iowa are also deposits in glacial waters and show the same characteristics as the latter. But they were deposited at a considerable distance from the continental ice-sheet.

These materials are also characterized by irregularity of sorting. Samples 34 to 47, inclusive, were taken more or less across bedding planes, so as to represent average conditions for each deposit. Only two samples out of fourteen are fairly well sorted, one being limited to five grades, the other to seven. Sample 35 may be said to have four maxima; samples 34, 38, 45, and 46 have three, and 36 and 47 have two. In averaging the admixtures in such materials it is necessary to select an arbitrary maximum believed to contain materials deposited under somewhat similar conditions in all cases. The result shows eight grades of admixtures on either side of the maximum; but the coarse admixtures are nearly twice the size of the fine, the grades farthest removed from the maximum showing the greatest difference in these samples, as was noted in the sands and gravels deposited in other glacial waters.

List of Samples in Table 4

24. Terrace gravel, Drummond, Illinois.
25. Terrace material, Government Island, Rock Island, Illinois.
26. Terrace gravel, Drummond, Illinois.
27. Terrace gravel from a low terrace in Bureau creek, Bureau, Illinois.
28. Terrace gravel from Government Island, Rock Island, Illinois.
29. Terrace gravel from Government Island, Rock Island, Illinois.
30. Terrace gravel, Putnam, Illinois.
31. Terrace gravel, Putnam, Illinois.
32. Terrace gravel, Putnam, Illinois.
33. Somewhat cross-bedded sand in a terrace of the Mississippi, Rock Island, Illinois.
34. Sand taken across the oblique lamination of the sand in a terrace, Rock Island, Illinois.
35. Terrace gravel, Putnam, Illinois.
36. Terrace sand from the Government Island, Rock Island, Illinois.
37. Terrace material, east of Davenport, Iowa.

Materials from single layers in terrace sands.—Eight samples were taken from single layers in banks of terraces. In their mechanical composition these so closely resemble the materials taken from single layers in materials deposited in glacial waters that they are chiefly interesting as testifying to the similarity of the physical conditions attending their deposition and to the validity of the inference that these analyses are an index of physical conditions.

List of Samples in Table 5

38. Terrace sand from a single layer, Port Byron Junction, Illinois.
39. Sand from a coarse layer in a terrace, Rock Island, Illinois.
40. Sand from the coarsest part of an oblique layer in a terrace, Rock Island, Illinois.
41. From the middle of an oblique layer in a terrace, Rock Island, Illinois.
42. Sand from the finest part of a layer in the cross-bedded sand of a terrace, Rock Island, Illinois.
43. Sand from a fine stratum in a terrace, Davenport, Iowa.
44. Sand from a fine layer in oblique bedding in a terrace, Rock Island, Illinois.
45. Sand from a homogeneous stratum of a terrace, Rock Island, Illinois.

Silts in terraces of the Mississippi.—Ten samples of silt, laid down by the Mississippi during the waning stages of the Wisconsin ice, were collected from some remnants yet left of the Wisconsin terrace in the valley of the river near Clinton and Davenport, in Iowa. Number 49 in the analyses is a sample taken across the bedding planes in this silt. All the others are taken from single layers in the deposit. There is con-

siderable variation in their composition. The maximum ingredient is coarse silt in the coarsest sample and very fine silt in the finest sample, showing a range through four grades.

List of Samples in Table 6

46. Glacial silt from a single layer, Clinton, Iowa.
47. Glacial silt from a single coarse layer, Clinton, Iowa.
48. Glacial silt, coarse and fine layers mixed, Davenport, Iowa.
49. Glacial silt from a single coarse layer, Davenport, Iowa.
50. Glacial silt from a single layer, Clinton, Iowa.
51. Glacial silt from a single layer of fine texture, Clinton, Iowa.
52. Glacial silt from a single layer, Clinton, Iowa.
53. Glacial silt from a single layer, Davenport, Iowa.
54. Glacial silt from a fine layer, Davenport, Iowa.
55. Glacial silt from a single layer of fine texture, Clinton, Iowa.

Sediments in present streams.—Some samples have been taken of sediments made in streams, where the conditions of sedimentation are somewhat better known than in the case of terrace deposits and deposits in glacial waters. The composition of these samples is best presented in four groups:

1. Gravel and sand in small streams.
2. Silt in small streams.
3. Gravel and sand in large streams.
4. Silt in large streams.

These deposits are formed under a great diversity of conditions, and the few analyses made do not adequately represent the great number of variations of deposits. Especially is this true of the coarser deposits such as gravel and shingle. It is not believed that there is a sufficient number of analyses to show the true characteristic distribution of the admixtures in the average of all these samples. Nevertheless, these samples show a similarity to the terrace and glacial deposits of the same class.

Sediments in small streams.—In the coarser deposits in small streams, neglecting the grade next below the maximum, there is an excess of coarse admixtures. It is probable that the precise maximum, as we may call that diameter which would divide the materials in these samples in two equal parts, lies in this case nearer the lower limit of the maximum grade than the higher limit.

In four samples of alluvial silt, collected in small streams, it appears that these silts have not had time to be separated from coarser materials as thoroughly as is common in most other silts. The coarser admixtures exceed the finer by 13.5 per cent.

List of Samples in Table 7.

56. Limestone gravel from Barton Creek, Austin, Texas.
57. Limestone gravel from Barton Creek, Austin, Texas.
58. Recent gravel in the bed of a creek, Linwood, Iowa.
59. Sand from the bed of Hat Creek, South Dakota.
60. Recent gravel in the bed of a creek near Linwood, Iowa.
61. Sand from a creek north of Linwood, Iowa.
62. Sand from the bed of Totogatic Once, Douglas County, Wisconsin.
63. Sand from ripples forming under water in a creek, Buffalo, Iowa.
64. Sand in the bed of a creek near Linwood Springs, Iowa.
65. Sand from a creek, Linwood, Iowa.
66. From a heap of sand laid down on an alluvial flat by a creek during a flood, Linwood, Iowa.
67. Sand deposited on the alluvial flat of a creek during a flood, Linwood, Iowa.
68. Sand in a creek five miles north of Ardmore, South Dakota.
69. Recent sand in a creek five miles north of Ardmore, South Dakota.

List of Samples in Table 8

70. Recent alluvium, Baltimore, Maryland.
71. Recent silt from a creek five miles north of Ardmore, South Dakota.
72. Alluvium from a small stream, Baltimore, Maryland.
73. Silt from Canton Hollow, Baltimore Harbor, Maryland.

Drifted sediments in large streams.—In 27 samples of sediments of the coarser kinds in large streams, it is evident that there are great differences in sorting. More than 1 per cent to each grade occurs in only three grades in the best sorted samples, while extreme imperfection of sorting has resulted in the distribution of such quantities through nine grades in one of these samples. On the average, more than 1 per cent is found scattered through five and a half grades, and all measurable ingredients are scattered in about six and a half grades. In less than half of the samples the admixtures form two decreasing series on both sides of a single maximum, for 14 samples show one secondary maximum, while two samples show two secondary maxima. In a general average there is a slight excess of finer admixtures, but there is nevertheless a very slight minor maximum in the coarse admixtures five grades distant from the principal maximum. In the average more than 1 per cent is found in eight grades, while appreciable quantities of less than 1 per cent are found in three more grades of coarse admixtures and in two additional grades of fine admixtures—that is, to say, quantities exceeding 0.1 per cent are distributed through 13 grades.

List of Samples in Table 9

74. Gravel from the bank of the Mississippi River, Davenport, Iowa. The sample contains many limestone pebbles of local origin.
75. Holy Cross Mission, 200 miles above mouth of Yukon River, Alaska.
76. Selkirk, Yukon River, Alaska, 200 miles above Klondike.
77. Tanana Station, Yukon River, Alaska.
78. Selkirk, Yukon River, Alaska.
79. Dunraven, Klondike River, Alaska.
80. Gravel from the bank of the Mississippi River, Davenport, Iowa. The sample contains much limestone of local origin.
81. River bank gravel, Davenport, Iowa. The sample contains much limestone, as above.
82. Sand from the north bank of the Mississippi River, New Boston, Illinois.
83. Sand from the bottom of the Mississippi River, Rock Island, Illinois.
84. From the bottom of the Mississippi River, near an island, southeast from Buffalo, Iowa. The bottom was perhaps being eroded.
85. Beach sand thrown up by boat waves, Buffalo, Iowa.
86. Recent river sand from the Mississippi River near the north bank of the Government Island, Rock Island, Illinois.
87. From the bottom of the Mississippi River, Buffalo, Iowa.
88. From the bottom of the Mississippi River during a flood, Buffalo, Iowa.
89. Rampart, Yukon River, Alaska.
90. Beach sand, Rock Island Harbor, Rock Island, Illinois.
91. Sand from the forming beach in the Mississippi River, Davenport, Iowa.
92. Sand from the beach of an island in the Mississippi River, Buffalo, Iowa.
93. Skagua, Alaska. In river coming down in bay, $1\frac{1}{2}$ miles from bay.
94. Recent alluvial sand, Mississippi River bank, Davenport, Iowa.
95. Sand bank on an island in the Mississippi River, Buffalo, Iowa.
96. Beach sand from the Mississippi River, Rock Island, Illinois.
97. Sand from the north bank of the Mississippi River, New Boston, Illinois.
98. Gravel from the bank of the Mississippi River, Davenport, Iowa. The sample contains much limestone of local origin.
99. Sand from the beach of the Mississippi River, Buffalo, Iowa.
100. Alluvium from the bottom lands east of Davenport, Iowa.

Silt from large streams.—Only four silts from large streams have been analyzed, and these are all from the Mississippi, in Illinois and in Iowa. Such deposits are among the most common in all parts of the world and it would be desirable to have more samples. They represent deposits formed during floods. Taken in connection with similar deposits from smaller streams, they may be considered as indicating a considerable uniformity in the sorting of the mechanical ingredients in such sediments. Most samples have secondary maxima in the coarse admixtures, or at least show a retardation in the decrease of quantities in that direction, four or five grades distant from the maximum.

List of Samples in Table 10

101. Alluvium, east of Davenport, Iowa.
102. From the bottom of the Mississippi River during a flood, Buffalo, Iowa.
103. Recent alluvium from the Mississippi River, Rock Island, Illinois.
104. From the bottom of the Mississippi River during a flood, Buffalo, Iowa.

Lake deposits.—Deposits formed in lakes are very scantily represented. In six beach sands from Lake Michigan it will be noted that the sorting out of all but three grades has been effected in three samples, and that in the other samples the quantities in the next distant grades are very small. Beach material is nearly always well sorted. Some recent lake silts have about the same composition as river silts. Another lake silt is a deposit in a glacial lake and is characterized by having a notable excess of medium clay and fine clay in the silt. This clay is probably derived from so-called "glacial milk." In common with other silts, these show a quite uniform sorting in different samples and in comparison with beach sand a much less perfect sorting, for no less than eight grades in each of these silts contain more than 1 per cent of the whole sample.

List of Samples in Table 11

105. Sand from the beach of Lake Michigan, Michigan City, Indiana.
106. Sand from the beach of Lake Michigan, Michigan City, Indiana.
107. Sand from the beach of Lake Michigan, Michigan City, Indiana.
108. Sand from the beach of Lake Michigan, Michigan City, Indiana.
109. Sand from the beach of Lake Michigan, Michigan City, Indiana.
110. Sand from the beach of Lake Michigan, Michigan City, Indiana.

List of Samples in Table 12

111. Deposit of clay on the bottom of Eau Claire Lake, Douglas County, Wisconsin.
112. Deposit of clay in Eau Claire Lake, Douglas County, Wisconsin.
113. "Red clay," of glacial origin, near Amminicon, Wisconsin.

Deposits in the sea—Classification.—Through the kindness of the curator of the United States National Museum, the author has secured some samples of marine sediments taken by various scientific expeditions that have been engaged in deep dredging in the Pacific as well as in the Atlantic. To the collection of such dredgings have been added some samples of material collected on sea beaches and some specimens of mud collected from anchors on various vessels. It seems most profitable to classify these marine sediments into the following divisions:

Beach gravels and sands.

Harbor silts.

Sediments on the landward side of the Atlantic continental shelf.

Sediments on the seaward side of the Atlantic continental shelf.

Sediments from the submerged west coast of America.

Sediments in the Bering Sea.

Sediments in the sea near volcanoes.

Sediments near the margins of ocean basins.

Beach gravel.—The few samples of materials sorted by beach action show the effectiveness of sorting by riparian currents. In six samples 99 per cent of the material is confined in three, or two, grades. In the averages of the seven samples the maximum grade contains 60 per cent. It will be recalled that beach material from lakes and rivers were better sorted than most other sediments in continental waters.

List of Samples in Table 13

- 114. Beach gravel, Olivia, Texas.
- 115. Gravel, mostly granite, Marblehead, Massachusetts.
- 116. Beach gravel, Olivia, Texas.
- 117. Ocean beach, Dutch Harbor, Alaska.
- 118. Beach gravel, Olivia, Texas.
- 119. Beach gravel, Olivia, Texas.
- 120. Ocean beach, Douglas Island, Alaska.

Silts in harbors.—Thirteen samples were taken from mud adhering to anchors of vessels lying in the harbor of Baltimore in February, 1893. The mud represents the sediments in the places where the anchors had last been lifted. Information on this point was obtained in each case from the captains of the ships from which the samples were obtained. Silting is going on in most harbors. Harbor waters are quiet. As a class these sediments are finer in their mechanical composition than any other marine sediments examined. The chief ingredient is very fine sand in one sample taken from near Salem, Massachusetts; in five samples it is coarse silt; in three it is medium silt, and in four it is fine silt. In the assortment of their admixtures the samples resemble each other quite closely. Excepting the coarsest sample, no less than six grades contain more than 1 per cent of the whole sample. In the general averages of the admixtures, the coarse grades decrease a little more rapidly than the fine for the five admixtures nearest to the maximum. This is believed to be a characteristic of sediments formed in waters with progressively slackening currents, which are waters that are overloaded. In the coarsest grades represented there is in several samples an increase in quantity away from the chief ingredients. This is in most cases due to

the presence of a small amount of cinders from the furnaces in steam craft, and does not necessarily characterize natural deposits in similar localities in the sea.

List of Samples in Table 14

121. Silt from the bottom of the harbor at Salem, Massachusetts (close to Marblehead).
122. Silt from the bottom of the harbor at Fortress Monroe, Virginia.
123. Silt from the bottom of the mouth of the James River, Virginia.
124. Silt from the bottom of the harbor at Port Antonio, $\frac{1}{4}$ mile from shore, West Indies.
125. Silt from the bottom of the Great Wicomico, Chesapeake Bay.
126. Silt from the bottom of the harbor at Hampton Roads, Virginia.
127. Silt from the bottom of the harbor at Fall River, Massachusetts.
128. Silt from the bottom of the harbor at Rio de Janeiro, South America.
129. Silt from the bottom of the harbor near Baltimore, Maryland.
130. Silt from the bottom of Providence Harbor, Rhode Island.
131. Silt from the bottom of the mouth of South River, Chesapeake Bay.
132. Silt from the bottom of the harbor at Stilton Quarantine Station, below Baltimore, Maryland.
133. Silt from the harbor at Sea Wall, Atlantic coast.

Deposits on the continental shelf in the West Atlantic.—Sedimentation on the continental shelf east of the United States is probably not as rapid now as in some earlier ages. It is perhaps less rapid than in the Gulf of Mexico. Some of the material in samples from this part of the sea is organic, consisting of fragments of shells and corals and of entire tests of foraminifera. These materials are evidently subjected to transportation and sorting by currents on the bottom of the sea. In the case of a few samples, where the organic ingredient was considerable and where it consisted of elements whose sorting appeared the least doubtful, corrections have been made to eliminate their quantities from the analyses. These corrections were made by ascertaining the ratios of these two ingredients in each grade by a separate count of the two in a part of the grade.

The 21 samples examined have their maxima distributed among various materials as follows:

	Diameter of grains in millimeters.	Number of samples.
Fine gravel.....	2 -1	2
Coarse sand.....	1 -1/2	3
Medium sand.....	1/2 -1/4	2
Fine sand.....	1/4 -1/8	4
Very fine sand.....	1/8 -1/16	4
Coarse silt.....	1/16-1/32	5
Medium silt.....	1/32-1/64	1

The composition of the deposits forming on the continental shelf are presented in two tables, the first containing material collected from the higher landward side of the shelf and the second containing samples from the outer seaward slope of the shelf. It will be seen that the samples taken from the outer part of the shelf contain more coarse material than the samples from nearer the land. This is no doubt due to the presence of tidal undercurrents, which must be strongest on the outer shoulder of the shelf. It appears that the irregularity of the topography of the sea-bottom near the outer border of the shelf would also tend to localize the currents and produce a greater variety of sediments. We find in these analyses only one sample which is of fine composition.

These samples show considerable variations in perfection of sorting. A few are as well sorted as beach material, as in case of samples 135, 142, 148; but most samples more nearly resemble stream sediments. Like these they have sometimes a secondary maximum. In a general average of the chief ingredient and admixtures in both groups, more than 1 per cent is found in eight grades, more than one-tenth per cent occurs in six coarse admixtures, and in five fine admixtures. A secondary maximum occurs in the fourth grade of the coarse admixtures.

List of Samples in Table 15

134. Mud and fine sand, about one-tenth in all organic, from the upper slope of the continental shelf. The analysis applies to the inorganic part only. Steamer *Albatross*; Station No. 871; latitude 40° 2' 54" north, longitude 70° 23' 40" west.
135. Coral sand, taken in channel between Cuba and Yucatan, 50 miles from land. Steamer *Albatross*; Station No. 2361; latitude 22° 8' 15" north, longitude 86° 51' 15" west; depth, 25 fathoms. January 30, 1885.
136. Quartz sand and shell fragments, on continental shelf, 30 miles south from Florida coast. The sample contains mostly quartz sand. Steamer *Albatross*; Station No. 2369; latitude 55° 1' 0" north, longitude 160° 12' 0" west; depth, 26 fathoms. February 7, 1885.
137. Coarse gray sand and gravel, containing white and black sand and mica, east of the south end of Labrador. Steamer *Trenton*; Station No. 3522; latitude 57° 58' 0" north, longitude 56° 34' 0" west; depth, 41 fathoms. August 4, 1893.
138. Green mud and fine sand, about one-third organic, taken on the continental shelf. Steamer *Albatross*; Station No. 2249; latitude 40° 11' 00" north, longitude 69° 52' 0" west; depth, 53 fathoms. September 27, 1884.
139. Green mud, about one-seventh organic, taken above the edge of the continental shelf, 70 miles from land, south of Massachusetts. Steamer *Albatross*; Station No. 2240; depth, 44 fathoms; sample taken in 1884; latitude 57° 0' 0" north, longitude 153° 18' 0" west.

140. White coral from close to the northeast coast of Cuba. The sample is about one-third mechanical. Steamer *Albatross*; Station No. 2352; latitude $22^{\circ} 35' 0''$ north, longitude $84^{\circ} 23' 0''$ west; depth, 460 fathoms. January 21, 1885.
141. Green mud and fine sand, containing very little organic matter, taken 200 miles east of Patagonia. Steamer *Albatross*; Station No. 2769; latitude $45^{\circ} 22' 0''$ south, longitude $64^{\circ} 20' 0''$ west; depth, $51\frac{1}{2}$ fathoms. January 15, 1888.

List of Samples in Table 16

142. Coarse gray sand, taken on outer border of the continental shelf. The sample consists of mainly ferruginous quartz sand, with no organic material. Steamer *Albatross*; Station No. 2296; latitude $35^{\circ} 35' 20''$ north, longitude $74^{\circ} 58' 45''$ west; depth, 27 fathoms. October 20, 1884.
143. Green mud, about 2 to 3 per cent organic material (*Globigerina*), on the slope of the continental shelf. Steamer *Albatross*; Station No. 2233; latitude $38^{\circ} 36' 30''$ north, longitude $73^{\circ} 6' 0''$ west; depth, 630 fathoms. September 12, 1884.
144. Broken shells. All sand, much clear quartz sand, taken about 12 miles east of Newfoundland. Steamer *Albatross*; Station No. 2447; latitude $46^{\circ} 26' 0''$ north, longitude $49^{\circ} 42' 0''$ west; depth, 39 fathoms. June 25, 1885.
145. From the bottom of the Atlantic on the edge of the continental shelf. Green mud and sand, with some organic fragments. These make about one-fourth of the sample. The analysis applies to the inorganic part of the sample only. Steamer *Albatross*; Station No. 2251; latitude $40^{\circ} 22' 17''$ north, longitude $69^{\circ} 51' 30''$ west.
146. Fine white coral sand, one-fifteenth not sorted, organic, from some 15 miles east of Yucatan. Steamer *Albatross*; Station No. 2358; latitude $20^{\circ} 19' 0''$ north, longitude $87^{\circ} 3' 30''$ west; depth, 222 fathoms. January 29, 1885.
147. Coral sand, black specks, broken shells, mostly organic, but apparently mechanically sorted. Steamer *Albatross*; Station No. 2313; latitude $32^{\circ} 53' 0''$ north, longitude $77^{\circ} 53' 0''$ west; depth, 99 fathoms. January 5, 1885.
148. Gray sand with black grains, containing about one-fourth organic material (*Globigerina*), taken from the upper border of the continental shelf, about 60 miles from land. Steamer *Albatross*; Station No. 2614; latitude 34° north, longitude 76° west; depth, 168 fathoms.
149. Green mud, containing 50 per cent inorganic material, taken on the slope of the continental shelf. Steamer *Albatross*; Station No. 2263; latitude $37^{\circ} 8' 0''$ north, longitude $74^{\circ} 33' 0''$ west; depth, 430 fathoms. October 18, 1884.
150. Dark gray mud. Gravel and sand, with some crinoid fragments, which are not counted in the grades of the analyses. On the upper slope of the continental shelf. Steamer *Albatross*; Station No. 2586; latitude $39^{\circ} 2' 40''$ north, longitude $72^{\circ} 40' 0''$ west; depth, 328 fathoms. September 20, 1885.

151. Gray ooze. Ooliths and various organic remains not counted in the analyses. On slope of continental shelf. Steamer *Albatross*; Station No. 2731; latitude $36^{\circ} 45' 0''$ north, longitude $74^{\circ} 28' 0''$ west; depth, 781 fathoms. October 25, 1886.
152. Foraminiferal sand and mud, one-tenth organic and not sorted, taken on lower part of slope of continental shelf, southeast of New York. Steamer *Albatross*; Station No. 2094; latitude $39^{\circ} 44' 30''$ north, longitude $71^{\circ} 4' 0''$ west; depth, 1,022 fathoms. September 21, 1883.
153. Gray mud. Much organic material, such as shell fragments, crinoids, and rhizopods, not included in the analyses. Steamer *Albatross*; Station No. 2584; latitude $39^{\circ} 5' 30''$ north, longitude $72^{\circ} 23' 20''$ west; depth, 541 fathoms. September 19, 1885.
154. Dark green mud, much organic (*Globigerina*) not counted, on the slope of the continental shelf. Steamer *Albatross*; Station No. 2729; latitude $36^{\circ} 36' 0''$ north, longitude $74^{\circ} 32' 0''$ west; depth, 679 fathoms. October 25, 1886.

Sediments on the submerged west slope of the west coast of America.—Ten samples came from the relatively steep submerged slope of the American continent in the Pacific. These show some extreme differences in the perfection of sorting. Some mud taken not far from the mouth of Salinas River off the coast of California has no less than nine grades which contain more than 1 per cent. In another sample 98 per cent are contained in two grades. This was taken 10 miles out from Cape Flattery, outside of where tidal currents sweep up and down the Strait of Juan de Fuca. On the whole and in their averages these samples resemble the materials from the continental shelf in the Atlantic, but contain a decidedly smaller amount of gravel and sand. It is believed this is due to the lesser strength of tidal undercurrents in the western sea.

List of Samples in Table 17

155. Yellow sand and mud from 15 miles southwest of the coast of California, on the slope of the continental shelf. The sample contains fragments of shells, black and white sand, and mica scales. Steamer *Trenton*; Station No. 3187; latitude $36^{\circ} 14' 0''$ north, longitude $121^{\circ} 58' 40''$ west; depth, 288 fathoms. April 3, 1890.
156. Gray sand, all inorganic, on the continental shelf, 10 miles from the coast of the northwest corner of the United States. Steamer *Albatross*; Station No. 2872; latitude $48^{\circ} 17' 0''$ north, longitude $124^{\circ} 52' 0''$ west; depth, 38 fathoms.
157. Yellow sand and mud containing magnetite, mica scales, some black grains, with plates and spines of echinoderms. Steamer *Trenton*; Station No. 3187; latitude $36^{\circ} 14' 0''$ north, longitude $121^{\circ} 58' 40''$ west; depth, 298 fathoms. April 3, 1890. From 10 miles west from the shore, off the middle of California.

158. Gray sand, mud, close to land, California coast. Steamer *Trenton*; Station No. 3478; latitude $36^{\circ} 44' 45''$ north, longitude $120^{\circ} 57' 0''$ west; depth, 68 fathoms. April 26, 1893.
159. Fine gray sand, 15 miles from the shore, west coast of Washington. Steamer *Trenton*; Station No. 3046; latitude $46^{\circ} 48' 30''$ north, longitude $124^{\circ} 28' 0''$ west; depth, 48 fathoms. June 7, 1889.
160. Mud from 20 miles west from the coast of southern California, on the border of the continental shelf. Steamer *Trenton*; Station No. 2891; latitude $34^{\circ} 25' 0''$ north, longitude $120^{\circ} 42' 0''$ west; depth, 233 fathoms. January 5, 1889.
161. Green mud, all inorganic, taken on continental shelf about 10 miles from the coast northwest of San Francisco, California. Steamer *Trenton*; Station No. 3165; latitude $37^{\circ} 59' 45''$ north, longitude $123^{\circ} 8' 35''$ west; depth, 50 fathoms. March 23, 1890.
162. Green mud containing one-third inorganic material, taken 8 miles east of the east coast of Lower California. Steamer *Albatross*; Station No. 3007; latitude $25^{\circ} 27' 30''$ north, longitude $110^{\circ} 50' 30''$ west; depth, 362 fathoms.
163. Green mud from 25 miles southwest of coast of southern California, on slope of continental shelf. Steamer *Trenton*; Station No. 3195; latitude $35^{\circ} 14' 0''$ north, longitude $121^{\circ} 7' 0''$ west; depth, 252 fathoms. April 5, 1890.
164. Brown ooze, consisting of about one-third organic material, taken 50 miles west of coast of Washington. Steamer *Trenton*; Station No. 2871; latitude $46^{\circ} 55' 0''$ north, longitude $125^{\circ} 11' 0''$ west; depth, 559 fathoms. September 23, 1888.

Deposits in the Bering Sea.—In Bering Sea we have a wide expansion of a shallow continental shelf where sediments are brought by the drainage of the adjacent land and by volcanoes in the sea. The depths at which 11 samples were taken vary only from 13 to 78 fathoms. Seven out of the 11 samples have the maximum composed of fine sand. This is the material around which the grades in the samples from the continental shelf in the west Atlantic are most closely grouped. In two samples the chief ingredient consists of very fine sand, in one it is coarse silt, and in one medium silt. Three of the coarsest samples are exceptionally well sorted, having each only two grades that contain more than 1 per cent of the whole sample. Two samples have a secondary maximum in the fine admixtures. These samples resemble the deposits on the Atlantic continental shelf, but are slightly more uniform in their composition. They contain more magnetic grains and much less organic material.

List of Samples in Table 18

165. Gray sand with black specks, some magnetic material, from the Bering Sea, 200 miles from land. Steamer *Trenton*; Station No. 3559; latitude 56° 56' 0" north, longitude 169° 52' 0" west; depth, 39 fathoms. September 3, 1893.
166. Black, mainly quartz, sand, 20 miles from Kadiak Island. Steamer *Albatross*; Station No. 2854; latitude 56° 55' 0" north, longitude 153° 4' 0" west; depth, 60 fathoms. August 10, 1888.
167. Fine gray sand containing only a trace of organic material. Sample taken 300 miles south of Bering Strait and 30 miles southwest of Nunivak Island. Steamer *Trenton*; Station No. 3515; latitude 59° 59' 0" north, longitude 167° 53' 0" west; depth, 13 fathoms. August 2, 1892.
168. Fine gray sand containing much magnetite from 25 miles south of west end of Alaska Peninsula, on the continental shelf. Steamer *Albatross*; Station No. 2847; latitude 55° 8' 0" north, longitude 160° 12' 0" west; depth, 48 fathoms. July 31, 1888.
169. Green mud, fine sand, with much magnetite, from 80 miles east of Pribilof Islands, Bering Sea. Steamer *Trenton*; Station No. 3490; latitude 56° 47' 0" north, longitude 173° 14' 0" west; depth, 78 fathoms. July 13, 1893.
170. Green mud, fine sand. Sand one-half dark colored, mostly quartz. From 15 miles southeast of Pribilof Islands. Steamer *Trenton*; Station No. 3492; latitude 56° 32' 0" north, longitude 171° 50' 0" west; depth, 70 fathoms. July 14, 1893.
171. Green mud and some magnetite grains from 150 miles from land. Steamer *Trenton*; Station No. 3539; latitude 56° 34' 0" north, longitude 167° 19' 0" west; depth, 57 fathoms. August 8, 1893.
172. Green mud and sand with some few magnetite grains, mostly quartz grains, from 100 miles north of Alaska Peninsula, Bering Strait.
173. Fine sand and green mud containing quartz grains with some magnetite from 900 miles from land, in Bering Sea. Steamer *Trenton*; Station No. 3513; latitude 58° 27' 0" north, longitude 169° 8' 0" west; depth, 35 fathoms. August 1, 1893.
174. Green mud, taken 20 miles south of Kadiak Island, south of Alaska. Steamer *Trenton*; Station No. 2855; latitude 57° 0' 0" north, longitude 153° 18' 0" west; depth, 69 fathoms. August 10, 1888.
175. Black sand containing some magnetic material from 5 to 10 miles north of large island west of Isonotski Straits. Steamer *Trenton*; Station No. 3265; latitude 55° 16' 30" north, longitude 163° 52' 45" west; depth, 38 fathoms. June 25, 1890.

Deposits in the sea near volcanoes.—Six samples were taken in the sea at points not far distant from volcanoes. These resemble other deposits in the deeper sea, with the exception that they contain some coarse material that consists of scoriæ of local volcanic origin. This makes secondary maxima in three of the analyses and retards the dim-

inution of the percentages in the distant coarse admixtures in two of the other samples. None are well sorted.

List of Samples in Table 19

176. Brown mud with black specks, containing many magnetic grains, some pumice, and mostly quartz, from the middle of the Gulf of California; volcanoes to the west. Steamer *Trenton*; Station No. 3436; latitude $27^{\circ} 3' 40''$ north, longitude $110^{\circ} 53' 40''$ west; depth, 905 fathoms. April 22, 1891.
177. All inorganic; not far from volcanoes, 5 to 10 miles away. The largest fragments are vesicular pumice, and much of the fine is strongly magnetic. Steamer *Albatross*; Station No. 2841; latitude $54^{\circ} 18' 0''$ north, longitude $165^{\circ} 55' 0''$ west; depth, 56 fathoms.
178. Fine gray sand, gravel; all mechanically sorted and contains some magnetic materials; 150 miles from the shore north of the Alaska Peninsula. Steamer *Trenton*; Station No. 3498; latitude $56^{\circ} 13' 0''$ north, longitude $169^{\circ} 36' 0''$ west; depth, 142 fathoms. July 17, 1893.
179. Coarse black sand, gravel, rocks; some scorïæ and magnetite; from 3 to 50 miles from the north end of Unimak Island. Steamer *Trenton*; Station No. 3324; latitude $53^{\circ} 33' 50''$ north, longitude $167^{\circ} 46' 50''$ west; depth, 109 fathoms. August 20, 1890.
180. Green mud, all inorganic. Sample contains some volcanic dust and scorïæ. Volcanoes 50 miles off. Steamer *Albatross*; Station No. 3324; latitude $53^{\circ} 37' 10''$ north, longitude $167^{\circ} 50' 10''$ west; depth, 284 fathoms.
181. Dark gray sand containing quartz with some mica; the coarsest part organic; from 300 miles west of the Azores. Steamer *Albatross*; Station No. 2585; latitude $39^{\circ} 8' 30''$ north, longitude $39^{\circ} 2' 40''$ west; depth, 328 fathoms. September 19, 1885.

Deposits near the margins of ocean basins.—Nine samples represent deposits in more open and deeper parts of the sea than those previously described. None of these come from any great or abyssal depths nor from very far out from the land. Even in some of these locations there must be currents of considerable strength sufficiently powerful to stir and sort coarse gravel. Sample 182 contains all grades from coarse sand to coarse gravel, but the main ingredients are very fine sand and coarse silt in most samples. The finest has for its chief ingredient fine silt. For the group the sorting is about the same as we find in lake silts or in harbor silts.

List of Samples in Table 20

182. Coral sand containing about one-third scorïæ, two-thirds shell fragments and foraminifera, and only a small part sand, taken a short distance east of the Galapagos Islands. Steamer *Albatross*; Station No. 2808; latitude $0^{\circ} 36' 30''$ north, longitude $89^{\circ} 19' 10''$ west; depth, 634 fathoms. April 4, 1888.

183. Brown ooze containing 6 per cent organic material, taken 60 miles east beyond the continental shelf. Steamer *Trenton*; Station No. 2715; latitude 38° 29' 30" north, longitude 70° 54' 30" west; depth, 1,753 fathoms.
184. Soft green mud. The sample contains various organic fragments with the inorganic, especially among the larger sizes. This analysis is partly estimated. From just below the continental shelf. Steamer *Albatross*; Station No. 2734; latitude 37° 27' 0" north, longitude 73° 53' 0" west; depth, 841 fathoms. October 26, 1886.
185. Green mud; some is organic, and some concretionary material among the larger particles; taken some 40 miles from land, southwest of the southwest part of British Columbia, outside of the continental shelf. Steamer *Trenton*; Station No. 2860; latitude 51° 23' 0" north, longitude 130° 34' 0" west; depth, 876 fathoms. August 31, 1888.
186. Gray ooze from the outer part of the continental shelf, west part of the Atlantic. Mud and fine sand, with much organic material, which does not affect the analysis. Steamer *Fish Hawk*; Collections No. 871; Station No. 2221; latitude 39° 5' 30" north, longitude 70° 44' 30" west; depth, 1,525 fathoms.
187. Brown ooze, about one-half organic (*Globigerina*), from 100 miles east of continental shelf. Steamer *Albatross*; Station No. 2712; latitude 38° 20' 0" north, longitude 70° 7' 30" west; depth, 1,867 fathoms. September 17, 1886.
188. Gray ooze, about one-third organic, from south of the continental shelf, Aleutian Islands. Steamer *Trenton*; Station No. 1138; latitude 52° 40' north, longitude 166° 35' west; depth, 2,257 fathoms. July 21, 1888.
189. Green mud, sand; 120 miles west of south boundary of California. Steamer *Trenton*; Station No. 3627; latitude 32° 44' 0" north, longitude 119° 32' 0" west; depth, 776 fathoms. April 13, 1896.
190. Gray mud, outside of the continental slope, beyond the mouth of the Mississippi River. Steamer *Albatross*; Station No. 2382; latitude 28° 19' 43" north, longitude 88° 1' 30" west; depth, 1,255 fathoms. March 3, 1885.

WIND DEPOSITS⁴

Classification.—It appears that all materials owing their present position and mechanical composition to the action of the atmosphere may be referred to some one of four categories. These are lag gravels, or coarse residual deposits in the rear of sand dunes and on desert lands; dune sand; fine sand, accumulating in the lee of drifting dunes, and dust.

Lag gravels.—In many places where atmospheric erosion is going on streaks of gravel are to be seen partly covering the ground. Most often this gravel forms a thin veneer, which partly protects the ground from further erosion. Though the present position of this material is due to

⁴The following summary of descriptions of wind deposits is abbreviated from my earlier paper already mentioned.

the action of the wind, it has not been transported very far. The deposits from which it has been derived are never far away. Commonly it is a bank of sand, part of which has been removed. The finer grades have been blown away, exposing these larger fragments to the force of the wind, which apparently moves them by undermining and rolling. It is evident that the coarseness of this gravel renders it much less subject to the action of the winds than the finer materials. Occasionally it may be found partly or wholly covered by finer materials, but on the whole it is continually left in the rear of these, which follow the winds with greater promptness. Only ten samples have been examined. These were collected at eight different localities in the central part of the United States. It is not likely that these few samples adequately represent the composition of similarly formed deposits in other localities. The largest rock fragment in the lot measured only a little over eight millimeters in its longest diameter. It was part of a sample consisting of flat chips of a hard shale. Pebbles over four millimeters in diameter were present in four of the samples. All the other samples, with one exception, had pebbles over two millimeters in diameter. The different grades are rather indiscriminately mingled in a manner determined by the caprices of the wind and by the variability of the materials on which the winds have worked. Five of the samples have two maxima each. The chief ingredients vary from fine gravel through coarse and medium sand to fine sand. In three of the samples 90 per cent of the weight is distributed among five different grades; in six among four grades, and in one among three. In an average of all ten samples 90 per cent of the weight is distributed among five grades. The highest maximum in any sample is 68 per cent and the lowest is 25. The average height of the highest maxima is 40 per cent.

List of Samples in Table 21

191. Chips of shale, Edgemont, South Dakota.
192. From a "blow-out," Hooppole, Illinois.
193. From a "blow-out," Hooppole, Illinois.
194. From north of Mineral, Illinois.
195. From the rear of a dune, Michigan City, Indiana.
196. From the bottom of a "blow-out," Alliance, Nebraska.
197. From the rear of a dune, Michigan City, Indiana.
198. From wind-blown ground, Ardmore, South Dakota.
199. From the rear of a dune, New Boston, Illinois.
200. From a "blow-out," Alliance, Nebraska.

Coarse drifting sand.—Lag gravels graduate imperceptibly into coarse blown sand, which in the field always lies in front of the gravels, follow-

ing the direction of the prevailing winds. Farther in this direction the coarse sand becomes in turn finer and finer, until the main deposit is reached, where it always consists of grains of a more uniform size. In fact, the main bulk of all sand drifts large enough to be called dunes have been found to contain only subordinate proportion of sand grains measuring more than one-fourth or less than one-eighth of a millimeter in diameter.

Sand coarser than typical dune sand is present as a maximum ingredient only in superficial layers of no very great thickness, which lie on the rear slopes of dunes. It forms an intermediate series between typical dune sand and lag gravels, and it is capable of being rolled rather than lifted by the winds. This is indicated by the circumstance that it is often the main ingredient on the crests of wind ripples, being heavy enough to remain resting in this exposed position, while the finer dune sand is lifted to the upward slope of the next ripple. It differs from the lag gravels in being light enough to be rolled up a gentle slope and to be moved without any undermining taking place. Eleven samples of such rolling blown sand, as it may be called, have been collected and examined. Its composition is much more uniform and regular than that of lag gravels. The proportions of the different grades arrange themselves in all the samples in two decreasing series on either side of a maximum which in three cases consists of coarse sand and in eight cases of medium sand. In one sample the maximum grade constitutes 85 per cent of the whole sample. The smallest maximum is 34 per cent. All the maxima average 50 per cent in the 11 samples. Ninety per cent of each sample is distributed among only three grades in nine of the samples and among four grades in the other two.

List of Samples in Table 22

201. Rear slope of a dune, Alliance, Nebraska.
202. Rear slope of a dune, Tampico, Illinois.
203. Rear slope of a dune, New Boston, Illinois.
204. Rear slope of a dune, Alliance, Nebraska.
205. Rear slope of a dune, Alliance, Nebraska.
206. Rear slope of a dune, Hooppole, Illinois.
207. Rear slope of a dune, Hooppole, Illinois.
208. Rear slope of a dune, Hooppole, Illinois.
209. Sand drift, Griggs County, North Dakota.
210. Sand drift, Griggs County, North Dakota.

Dune sand.—The sand which constitutes the main body of dunes has been found remarkably uniform in its mechanical composition. Thirty-eight samples have been analyzed, coming from 11 different localities.

These localities it will be well to briefly describe, together with the sand from each.

On the north side of the Mississippi River, at New Boston, in Illinois, an ancient terrace is blown up into a sand ridge about a mile in length. From all appearances the sand in these dunes has not yet traveled a half mile. The materials in the original terrace are quite heterogeneous in composition. The coarse grades have not yet had time to be entirely left behind, but appear in a small quantity in some of the dune sand. One of the samples was taken by skimming the surface on the crest of a ripple. This is unique among all the analyses of typical dune sand in having medium sand as its maximum ingredient. Had it been taken a little deeper it would have been more like the rest, for the coarser grains are least easily dislodged from this exposed position and remain, while the finer sand is blown away. Some coarse dust is still mixed in the sand at this place in one instance. All taken together and compared with sand from other places, these samples may be said to be imperfectly sorted, owing no doubt to the recency of the inception of the wind action in this locality.

The dunes on the southeast shore of Lake Michigan have furnished the materials for six analyses. These sand hills have been recently formed, and are largely made up of sand that is freshly supplied by present wave action on the shore of the lake. In this place also the coarse grades occur with the typical dune sand in small quantities on the very top and front slope of the hills; but there is practically no coarse dust to be seen, presumably because no such fine material is present in the beach sand. This locality and the previous are the only ones that furnish instances of dune sand having a secondary maximum in the coarser grades.

The bluffs facing the bottom lands of the Mississippi east of Cordova, in Illinois, are here and there being drifted by the northwest winds. Some sand taken from a small drift only a foot in height exhibits imperfect sorting like that observed in the sand from New Boston and Michigan City.

In Rice County, in the central part of Kansas, there is a tract of sand hills extending many miles along the Little Arkansas River. These are derived from underlying late Tertiary beds. Their extensive development shows that the wind has been at work here for some considerable time. The sand is correspondingly uniform and rock fragments of either extreme size are absent. One of the analyses exhibits the mechanical composition of a single thin lamina in the dune, evidently laid down under a uniform wind velocity. It is interesting as indicating, when

compared with the other analyses, the range of variation in the coarseness of the sand due to differences in the velocity of the wind. Evidently this is not very great.

At Folly's Cove, in Massachusetts, some beach sand is driven inland by the winds. The absence of fine particles in this sand is no doubt partly due to washing on the beach.

Some sand has been collected from small and freshly formed drifts on plowed fields and on the open prairie in the eastern part of North Dakota. The rather large amount of dust in all of these analyses is evidently due to the fact that the wind has just begun its work on surface deposits, which contain fine materials in some abundance.

Scattered dunes occur in the basin of the Green River, in Illinois. Though the superficial deposits here are but little affected by the action of the atmosphere now, the topography of several sandy belts in this valley indicates earlier deflation by the atmosphere. The sand is moderately well sorted.

Some years ago a drift of sand was blown up in a field near Lindsborg, Kansas. The soil in this place was composed of a sandy alluvium, which held very little fine material. No specially noteworthy feature appears in the mechanical composition of this sand.

The most extensive sand-hill region in the United States is probably found in the western part of Nebraska. Here the winds have been at work for a long time rearranging, shifting, and sifting extensive beds, which were formed in Pliocene and early Pleistocene time. Entire counties are covered by extensive ranges of sand hills, sometimes exceeding 300 feet in height. The bulk of the blown sand in this region largely exceeds that of any other locality from which any material has been collected. The lag gravels are conspicuously absent in the samples examined, nor do these contain more than a trifle of dust. It is the most uniformly sorted of all the sands described. Two of the samples were selected to represent the extremes of variation among a series of layers which were seen in an exposure with well defined bedding. One was taken from the coarsest seam which could be seen and the other from the finest. The difference in texture was quite apparent to the eye, as the seams appeared in the natural exposure, but it seems rather insignificant in the analyses.

South of Moline, Illinois, there are some drifts of sand in a remnant of an old terrace. This blown sand has not been carried farther than two or three hundred yards.

In the southern part of Henderson County, in Illinois, there is a range of sand hills which follows the bluffs of the Mississippi River. In

their topographic features these hills resemble sand dunes, but the activity of the winds seems to have come to a standstill at present except in a few places on the summits of the ridges. Two samples from this locality show a remarkably perfect sorting, though one of them, which was taken from a drifting cultivated field, carries the usual quantity of fine grades present in blown soils.

It will be noticed that in all these samples of dune sand, excepting the one collected by skimming the ridge of a ripple, the maximum ingredient is fine sand. In one instance 92 per cent consists of this grade, while in three cases it forms over 80 per cent of the bulk. Where lowest it forms 45 per cent, and it averages 65 per cent in all the sand examined. In three of the samples 90 per cent is distributed among four grades; in 22 among three grades, and in 13 between only two. Here also the admixtures arrange themselves in two series, decreasing on either side of the maximum. The coarse admixtures form a less rapidly decreasing series than the fine, the former extending over five grades in the general average and the latter over only three grades. The extension of either is evidently diminished by prolonged wind action, which results in more perfect elimination of grains near either extreme.

List of Samples in Table 23

211. Rear slope of ripples in dune sand, New Boston, Illinois.
212. Dune sand, New Boston, Illinois.
213. Top of ripple on dune sand, New Boston, Illinois.
214. Front slope of dune, New Boston, Illinois.
215. Upper rear slope of a dune, Michigan City, Indiana.
216. Dune sand, Michigan City, Indiana.
217. Typical dune sand, Michigan City, Indiana.
218. Near the crest of a dune, Michigan City, Indiana.
219. From the crest of a dune, Michigan City, Indiana.
220. From the top of a dune, Michigan City, Indiana.
221. Blown sand from the river bluffs, Cordova, Illinois.
222. From the front slope of a dune, Rice County, Kansas.
223. From the rear slope of a dune, Rice County, Kansas.
224. From a single seam in the front slope of a dune, Rice County, Kansas.
225. Dune sand, Folly's Cove, Massachusetts.
226. Dune sand, Folly's Cove, Massachusetts.
227. Blown sand in a field, Barnes County, North Dakota.
228. Blown sand in a field, Cooperstown, Griggs County, North Dakota.
229. Blown sand in a field, Steele County, North Dakota.
230. Blown sand, Steele County, North Dakota.
231. Blown sand, Griggs County, North Dakota.
232. Dune sand, Tampico, Illinois.
233. Dune sand, Hooppole, Illinois.
234. Blown sand, Lindsborg, Kansas.

- 235. Dune sand, Alliance, Nebraska.
- 236. Front slope of dune, Alliance, Nebraska.
- 237. From a coarse layer in dune sand, Hyannis, Nebraska.
- 238. From a fine seam in dune sand, Hyannis, Nebraska.
- 239. From the rear slope of a small dune near Moline, Illinois.
- 240. From the top of a small dune near Moline, Illinois.
- 241. From the top of a small dune near Moline, Illinois.
- 242. From the lower front slope of a small dune near Moline, Illinois.
- 243. From the top of a dune near Moline, Illinois.
- 244. From the upper front slope of a small dune, Moline, Illinois.
- 245. From the top of a small dune, Moline, Illinois.
- 246. From the lower front slope of a small dune, Moline, Illinois.
- 247. From a dune east of Carman, Illinois.
- 248. Blown field, Decorra, Illinois.

Incipiently blown sand.—Some specimens of sand were collected from widely distant places, where the wind has just begun to work on materials of quite diversified composition. In the following table one sample was collected in Kansas in a bottle placed about a foot above the ground in a drifting cultivated field, where the soil held gravel as well as clay; one was taken from the surface of a snow-drift in Maryland, where the deposit had blown from an exposure of Potomac sand of somewhat heterogeneous composition; one is from a gutter in the city of Baltimore, and was sifted out by the wind from the dust on a paved street; one is from the beach at Saint Augustine, in Florida, where such sand is reported to be tossed about by the sporting wind with particular ease, owing to the fact that the water has already effected a most favorable sorting, and one was collected in a small receptacle placed on a drifting railroad bed in the west part of Illinois. The chief ingredient in these sands is alike in all and is of the same grade as that found in dune sand.

List of Samples in Table 24

- 249. Incipiently blown sand, Lindsborg, Kansas.
- 250. Sand blown on a snow-drift, Baltimore, Maryland.
- 251. Sand blown in a gutter, Baltimore, Maryland.
- 252. Sand blown on the beach, St. Augustine, Florida.
- 253. Blown sand on a railroad bed, Carman, Illinois.

Lee sand.—In front of a dune drift and confluent with it there is generally a rippleless bench of sand, which has settled in the eddy in the lee of the larger drift.⁵ The sand in the lee drift, as it may be called, is found to be a little finer than the dune sand proper. Its grains have

⁵ Johannes Walther: *Die Denudation in der Wüste*, etcetera, p. 172, fig. 89. First edition.

been lifted a little higher, and that is the reason why they have been carried a little farther; but the difference is very slight, and consists merely in a change in the proportions of the percentages on either side of the maximum.

Four series of wind sediments have been taken from successively more distant points in front of dunes and sand drifts in Kansas, Illinois, and North Dakota. The analyses of these series show that the grains which approximate nearest to the dune sand in size are not carried very far. The samples from Rice County, in Kansas, and those taken near Moline, in Illinois, exhibit merely a decrease of the coarse admixtures and a corresponding increase in the fine admixtures for increasing distances within a range of 200 feet. In distances less than 200 feet the percentages of the fine ingredients increase from eight in the dune sand to 41 in the lee sand.

A series of samples taken in front of the sand drift at Lindsborg changes more rapidly, so that only 50 feet away 65 parts in a hundred consist of very fine sand. The dune at this place was much lower than the other, and this partly accounts for the rapid settling of the fine sand, which here had a very short distance to fall.

List of Samples in Table 25

- 254. From the lee of sand dunes, Rice County, Kansas.
- 255. From 6 feet in front of the lee drift of a dune, Rice County, Kansas.
- 256. From 15 feet in front of the lee drift of a dune, Rice County, Kansas.
- 257. From 24 feet in front of the lee drift of a dune, Rice County, Kansas.
- 258. From a small lee drift, Lindsborg, Kansas.
- 259. Ten feet in front of a small lee drift, Lindsborg, Kansas.
- 260. Fifty feet in front of a small lee drift, Lindsborg, Kansas.
- 261. Ten feet in front of a small dune near Moline, Illinois.
- 262. One hundred feet in front of a small dune near Moline, Illinois.
- 263. One hundred and sixty feet in front of a small dune, Moline, Illinois.

Dust—General discussion.—To determine the size of the particles that may readily be transported long distances by ordinary winds, we should examine the nature of the loads which these winds generally carry. I have collected a number of samples of such dust by different methods, under different conditions of deposition and from different localities.

Miscellaneous collections of dust.—Some of the dust samples collected for this study are sediments which have been carried by the atmosphere under more than ordinarily favorable circumstances and in currents of more than ordinary strength. Such is sand and dust stirred up from the

roadbeds by running railroad trains. The material which is lifted high enough to come in through the windows and doors of passenger coaches is mainly dust. Among 13 samples collected in coaches in different parts of the United States only one had as much as 17 per cent of fine sand, and one had less than 1 per cent. In five of these samples the maximum occurs in the grade of very fine sand, which is next in fineness to the maximum grade of the dune sand; in seven of the samples it occurs in the coarse dust, and in one it is in the next finer grade. The small percentages of the coarser grains is no doubt in part due to the reduced velocities of the currents entering the coaches. Analogous causes may have affected the perfection of the sorting in these samples, which varies considerably, ninety parts in a hundred being distributed among four grades in some instances and between only two in some; but the differences in the speed of the trains and the differences in the mechanical composition of the surface deposits along the railroad must also be taken into account. Nor was the sampling uniform. In some instances the dust was taken after heavy winds and in others during calm weather; in some cases it was gathered up from the window-sills, and in other cases from the seats in the coaches. Some of it was brushed from the wearing apparel of a passenger. Taking all these modifying circumstances into due consideration and remembering that the currents of wind which follow a running railroad train are quite as powerful as the currents next to the ground in the heaviest wind storm, the composition of this dust may be taken to indicate that fine sand is too heavy to be effectively kept from settling in such winds; that very fine sand and coarse dust are just on the limits of the size which is subject to effective suspension.

Similar inferences are made from the composition of some dust gathered on a window-sill 3 feet above the ground in a building at Yuma, in Arizona.

Volcanic dust forms another class of atmospheric sediments which are transported under unusually favorable conditions. It is launched from great heights, to which it never could have been raised by the convection currents of the lower part of the atmosphere, and it is carried by the upper currents, where transportation is much more swift than below. Nearest the volcanic outburst there is no maximum limit to the size of volcanic fragments which may fall, but beyond the distance of the influence of the projectile force, which seldom perhaps exceeds a dozen miles, their size is determined by the sorting action of atmospheric currents and hence will be a true exponent of the nature of this action. A sample of volcanic dust which fell on the coast of Norway,

following an eruption on Iceland, was obtained from the United States National Museum. This dust was carried a distance of 800 miles by the wind.

Some dust was collected close to wagon roads, where it was raised by passing vehicles and sifted as it fell by gentle winds. In dust of this kind, which fell 5 feet from the road, 23 per cent was fine sand and 11 per cent was composed of still coarser grains. In dust which fell 10 feet farther away there was only a little over 4 per cent of the coarse grades. In this sample very fine sand forms 31 per cent. Ten feet still farther out this grade is represented by less than 10 per cent. These grades evidently easily settle out of gentle atmospheric currents. Of particles which are less than one sixty-fourth of a millimeter in diameter there are only small quantities, presumably because such particles tardily settle even in ordinary low winds.

Dust which was swept by the wind from the banks and the bottom lands of the Minnesota River and lodged on the ice in its channel shows about the same composition as the average of the last samples.

Two samples of dust were collected in houses 4 miles away from blown sandy fields in North Dakota.

List of Samples in Table 26

264. Dust in a house four miles from a blown field, North Dakota.
265. Dust in a school-house four miles from a blown field, North Dakota.
266. Collected in a running railroad coach after a sandstorm in Arizona.
267. Collected in a running railroad coach in southern Minnesota.
268. Collected in a running railroad coach in Nebraska and Kansas.
269. Collected in a running railroad coach in New England.
270. Collected in a running railroad coach in North Dakota and Montana.
271. Collected in a running railroad coach in the Rocky Mountains and the Cascades.
272. Collected in a running railroad coach in Utah.
273. Collected in a running railroad coach in North Dakota after a storm.
274. Collected in a running railroad coach in North Dakota.
275. Collected in a running railroad coach in western Minnesota.
276. Collected in a running railroad coach in eastern Colorado.
277. Collected in a running railroad coach in Kansas.
278. Collected in a running railroad coach in Idaho and Washington.
279. From a window-sill in a house in Yuma, Arizona.
280. Volcanic dust from snow in Norway.
281. Dust taken 5 feet from a wagon road near Baltimore, Maryland.
282. Dust taken 15 feet from a wagon road near Baltimore, Maryland.
283. Dust taken 25 feet from a wagon road near Rock Island, Illinois.
284. Dust taken 25 feet from a wagon road near Baltimore, Maryland.
285. Dust collected from the ice on Minnesota River.

Dust collected by apparatus from the atmosphere.—One of the devices the writer used in collecting dust directly from the atmosphere consisted of some whisks of broom-corn smeared with glycerine and suspended from a pole 90 feet above the ground. The collecting was made on a bluff overlooking the Mississippi River at Rock Island, in Illinois. The whisks were taken down once a day and washed in water, which was allowed to stand until the dust had settled. This was then removed, dried, and ignited. One series of such samples was secured during the month of March, in 1895. These were mixed into five larger samples, each of which represented days with maximum hourly wind velocities ranging between fixed limits. The range of these velocities during the month was from 12 to 33 miles per hour, and the quantities of dust taken were roughly proportionate to the sixth power of these velocities, ranging from one-tenth of a gram to 50 grams. The analyses were imperfect in the coarsest grades and have been omitted. They do not indicate that there was any increase in the size of the particles transported during the days having the strongest wind, as might have been expected. The maximum in each of the samples occurs in the medium dust.

In June of the same year material was collected in the same manner and at the same place daily for one week, and a separate analysis was made of each catch. The maximum hourly velocities of the wind for each day ranged from 9 to 20 miles. In this case also there was a correspondence between the wind velocities and the quantities of the dust caught. On examining the analyses, it is seen that the coarse admixtures rather decrease than increase with the speed of the wind. The fine ingredients are quite as well represented for the days with high winds as for days with low winds.

Some dust was collected at the same place and at the same height by suspending two pieces of muslin held horizontally on a frame. The muslin was smeared with glycerine, to which the dust adhered. The catch was secured by washing and allowed to settle as before. One sample consisted of a mixture of daily catches taken during part of June and part of July, in 1895. These were thoroughly mixed before the analysis was made. Two samples which were taken, one on the upper cloth and one on the lower, on the nineteenth of August the same year, were separately examined, as was also some other material collected in the same manner under some trees in a grove about a quarter of a mile from the pole previously referred to. The dust taken in this way resembles perfectly that which was caught on the broom-corn.

Another device for collecting dust from the atmosphere consisted of a hollow cylinder, with apertures on the side for receiving the wind and

with strips of muslin suspended inside. These strips as well as the inner surface of the cylinder were washed once a week and adhering particles thus secured. Eight samples were taken by this method during the months of July, August, and September, in 1895. The cylinder was suspended at the same height and from the same flagpole as the broom-corn and the muslin previously mentioned. In this series of samples also there was a correspondence between the wind velocities and the quantities of dust caught, though not so well marked as in the other instances referred to. On the nineteenth of February, in 1896, when there was a high wind and much dust in the atmosphere over the Mississippi Valley, one more sample was taken in the cylinder, this time suspended only 10 feet above the ground.

All dust caught in the cylinder, excepting two samples, is coarser than that which was caught on adhesive surfaces. The maximum grade consists of coarse dust in the former, while in the latter it is medium dust. It appears that the slack wind was not retained in the cylinder long enough to allow the fine particles to settle. In this way the maximum has been transferred toward the coarse grades. It is to be inferred, also, that the coarsest particles caught on the adhesive surfaces would more frequently be rubbed and shaken off than the finest particles.

List of Samples in Table 27

- 286. Dust collected from the atmosphere in winds not exceeding 9 miles per hour.
- 287. Dust collected from the atmosphere in winds not exceeding 10 miles per hour.
- 288. Dust collected from the atmosphere in winds not exceeding 12 miles per hour.
- 289. Dust collected from the atmosphere in winds not exceeding 13 miles an hour.
- 290. Dust collected from the atmosphere in winds not exceeding 19 miles an hour.
- 291. Dust collected from the atmosphere in winds not exceeding 22 miles per hour.
- 292. Dust collected from the atmosphere in winds not exceeding 22 miles per hour.
- 293. Dust collected 90 feet above ground in Rock Island, Illinois, June and July, 1895.
- 294. Dust collected 10 feet above ground under trees, Rock Island, Illinois, September, 1895.
- 295. Dust from top cloth on flagpole, August 19, 1895, Rock Island, Illinois.
- 296. Dust from bottom cloth on flagpole, August 19, 1895, Rock Island, Illinois.
- 297. Dust collected in a hollow cylinder 90 feet above the ground at Rock Island, Illinois, summer of 1895; maximum wind velocity, 14 miles per hour.

- 298. Like the preceding; maximum wind velocity, 18 miles per hour.
- 299. Like the preceding; maximum wind velocity, 18 miles per hour.
- 300. Like the preceding; maximum wind velocity, 19 miles per hour.
- 301. Like the preceding; maximum wind velocity, 20 miles per hour.
- 302. Like the preceding; maximum wind velocity, 21 miles per hour.
- 303. Like the preceding; maximum wind velocity, 23 miles per hour.
- 304. Like the preceding; maximum wind velocity, 24 miles per hour.
- 305. Dust collected in a hollow cylinder 10 feet above the ground at Rock Island, Illinois, February 19, 1896.

Dust taken on surfaces above the ground.—Several analyses have been made of dust found adhering to surfaces of objects more or less elevated above the ground. Eight such samples were washed from the foliage of trees, on which appreciable deposits of dust may always be observed. The maximum grade in this material is medium dust, but the lesser weight and the smaller size of the particles of less than this size renders them less subject to dislodgment by the wind and by occasional shaking and rubbing of the leaves against each other. When collected in the early part of the summer, this dust is therefore found to be coarser than it is later on, owing to the more frequent removal of the coarser particles and the more persistent adhering of the finer particles. In some dust which was washed from the leaves of oak trees in the months of May and June, in 1895, there was about 20 per cent of fine dust, while in two samples taken in August and September there was a little over 30 per cent of the same ingredient, and in another sample, which was washed from leaves remaining on some trees in February, the fine dust was the maximum ingredient, making nearly 40 per cent of the whole sample. Four analyses are of dust taken on the bark of some trees, and two are of dust coming with rain-water from a house-roof. Such rough surfaces as these give a secure lodgment to grains of sand as well as dust. From the analyses it is quite evident that some coarse material is moved even by the gentle winds of the Mississippi Valley. It may be that many of these grains are raised by the aid of lighter objects to which they adhere, such as bits of straw and leaves; but their abundance in these last samples is best accounted for by the action of occasional strong convection currents and by the increased chances for larger grains to find lodgment on rough surfaces. This may be inferred from two analyses, one of which gives the composition of some dust collected from the trunk of a small tree by striking it repeatedly with a hammer, while the other shows the ingredients in the material which remained on the bark after this procedure and which was secured afterward by washing. The former has a small and the latter a large proportion of the admixtures on either side of the maximum ingredient. Aside from

the greater proportions of the extreme grades, which may be accounted for by the diminished proportionate chances of the grains of the maximum ingredient to find and maintain a secure lodgment, all of these samples resemble those collected on surfaces rendered adhesive by the application of glycerine.

List of Samples in Table 28

- 306. Dust shaken from the trunk of an oak, Rock Island, Illinois.
- 307. Dust in rain-water from the roof of a house, Rock Island, Illinois.
- 308. Dust from rain-water coming down on the trunk of an oak during a shower, Rock Island, Illinois.
- 309. Dust from the trunk of an oak, Rock Island, Illinois.
- 310. Dust in rain-water from the trunk of an oak, Rock Island, Illinois.
- 311. Dust washed from the trunk of an oak, Rock Island, Illinois.
- 312. Dust washed from some poplar leaves, Rock Island, Illinois.
- 313. Dust washed from the leaves of a hickory tree, Rock Island, Illinois.
- 314. Dust washed from the leaves of a linden tree, Rock Island, Illinois.
- 315. Dust washed from the leaves of an oak tree, Rock Island, Illinois, June, 1895.
- 316. Dust washed from the leaves of an oak tree, May, 1895, Rock Island, Illinois.
- 317. Dust washed from foliage of trees, La Salle, Illinois.
- 318. Dust washed from foliage of trees, New Bedford, Illinois.
- 319. Dust washed from dry leaves of oak trees, Rock Island, Illinois, February, 1895.

Shower dust.—Deposits of an impalpable dust are sometimes observed in the central States, especially during winter, when it is apt to fall on the snow. It generally appears after strong westerly winds, which have been called dust storms. Eighteen samples of such dust have been examined, and these represent six different storms. The coarsest fell in Kansas City in the summer of 1890. Nearly 60 per cent of its weight consists of coarse dust, and less than 30 per cent is medium dust. Two samples taken near Alta, in Iowa, come next to this in coarseness. An average of the two analyses has 52 per cent of coarse dust and 35 of the medium. This was collected during and after a heavy wind in the early part of June, in 1895.

Thirteen samples were gathered from the surface of ice and from snow at Rock Island, in Illinois, and these represent three different showers. One such shower occurred in the latter part of November, in 1894; one in the latter part of January, in 1895, and one in February, in 1896. Dust gathered on the ice of the Mississippi, close to land, contains comparatively large quantities of coarse admixtures, evidently derived from the ground close by, and the same is the case with some

material which had accumulated in a long crevice in the ice, across which the wind had been drifting after the deposit had settled. The dust taken near the center of the channel of the Mississippi River has less of the coarse admixtures, as does also that taken on snow. Over level areas, as out on the ice of the river away from the banks and on an open field, a greater proportion of fine dust is noticeable, due most likely to a more even progression of the atmosphere permitting more of its load to settle, while near places where timber or the relief of the land had set up convection currents less of the finer dust seems to have been able to come down. In the averages from each of these three showers the medium and the fine dust are present in nearly equal proportions and constitute from 74 to 87 per cent of the whole. In the samples collected on the ice there is nearly three times as much of the two grades of sand as in those taken on snow, owing, it seems, to the greater quantity of local drift raised by the wind from bare ground along the banks of the river.

A sample of dust was taken just west of Chicago soon after the shower which occurred in the latter part of February, in 1896. It contains a considerable admixture of local coarse fragments, but aside from this it is slightly finer than the average deposit from the same storm at Rock Island. Still another sample was collected at Maysville, in New York, after this storm. This also contains a small quantity of sand, but it is otherwise the finest of all the samples of the shower dust examined, having a larger percentage than the rest of all the grades containing particles less than one thirty-second of a millimeter in diameter.

List of Samples in Table 29

320. Shower dust from Kansas City, Missouri.
321. Shower dust from Alta, Iowa, June 7, 1895.
322. Shower dust from Alta, Iowa, June 8, 1895.
323. Shower dust on the ice of a small pond, Rock Island, Illinois, November, 1894.
324. Shower dust on the ice of the Mississippi, near its bank, Rock Island, Illinois, November, 1894.
325. Shower dust on the ice near center of channel of the Mississippi, Rock Island, Illinois, November, 1894.
326. Shower dust on the ice of the Mississippi, near bank, Rock Island, Illinois, January, 1895.
327. Shower dust on the ice of the Mississippi, near bank, Rock Island, Illinois, January, 1895.
328. Shower dust from a crack in the ice of the Mississippi, near channel, Rock Island, Illinois, January, 1895.
329. Shower dust on the ice of the Mississippi, near center of channel, Rock Island, Illinois, January, 1895.

- 330. Shower dust on the ice of the Mississippi, near bank, Rock Island, Illinois, January, 1895.
- 331. Shower dust from snow in timber, Rock Island, Illinois, February, 1896.
- 332. Shower dust on snow on top of bluff, Rock Island, Illinois, February, 1896.
- 333. Shower dust from snow near a ravine, Rock Island, Illinois, February, 1896.
- 334. Shower dust from snow close to a tree, Rock Island, Illinois, February, 1896.
- 335. Shower dust from snow on an open field, Rock Island, Illinois, February, 1896.
- 336. Shower dust, Chicago, Illinois, February, 1896.
- 337. Shower dust, Maysville, New York, February, 1896.

TABLES OF MECHANICAL ANALYSES

TILL

TABLE 1.—*Mechanical Composition of Till from the upper Mississippi Valley*

Names of Ingredients.	Size of diameter in millimeters.	1*	2	3	4	5	6	7	8
Large boulders.....	256-128.....	....	....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	1.6	....	....	.8	....	2.0	7.6	.5
Coarse gravel.....	8-4.....	8.4	.3	.2	3.9	.6	1.9	8.5	.9
Medium gravel.....	4-2.....	4.0	1.3	2.0	1.3	1.9	2.3	4.3	1.3
Fine gravel.....	2-1.....	2.9	1.8	2.9	2.2	2.7	3.5	2.3	1.6
Coarse sand.....	1-1/2.....	5.5	4.2	5.7	3.0	5.7	3.4	3.7	1.9
Medium sand.....	1/2-1/4.....	6.4	4.6	7.8	4.5	7.1	2.3	4.1	4.6
Fine sand.....	1/4-1/8.....	17.3	17.2	14.4	16.1	13.4	3.9	13.5	8.4
Very fine sand.....	1/8-1/16.....	11.9	22.4	13.0	17.6	13.2	7.5	11.5	7.8
Coarse silt.....	1/16-1/32.....	16.1	17.8	25.4	24.2	23.7	20.7	15.3	11.3
Medium silt.....	1/32-1/64.....	16.1	16.4	18.4	14.0	18.9	14.1	12.0	25.6
Fine silt.....	1/64-1/128.....	7.0	7.3	6.8	10.2	8.1	14.1	11.8	28.2
Very fine silt.....	1/128-1/256.....	1.2	4.5	2.5	1.4	2.9	1.6	3.5	4.4
Coarse clay.....	1/256-1/512.....	.3	1.4	.8	.4	1.2	4.2	1.0	1.8
Medium clay.....	1/512-1/1024.....	.2	.4	.4	....	.4	2.3	.8	.9
Fine clay.....	1/1024-1/2048.....	....	....	.2	....	.1	1.0	....	.1

* In this and the following tables these numbers refer to the corresponding numbers in the lists of samples.

WATER DEPOSITS

TABLE 2.—*Mechanical Composition of Gravels and Sands deposited in Glacial Waters*

[illegible]

TABLE 6.—*Mechanical Composition of Silts deposited by the Mississippi during the waning Stages of the Wisconsin Ice*

Names of ingredients.	Size of diameter in millimeters.	46	47	48	49	50	51	52	53	54	55
Large boulders.....	256-128.....	....	....	....	....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....	....	....	....	....	....	....
Coarse gravel.....	8-4.....	....	....	....	....	....	....	....	....	....	....
Medium gravel.....	4-2.....	....	....	....	....	....	....	....	....	....	....
Fine gravel.....	2-1.....	....	....	....	....	....	....	....	....	....	....
Coarse sand.....	1-1/2.....	tr.	tr.	....	....	tr.	....	....	....	....	....
Medium sand.....	1/2-1/4.....	tr.	.1	.1	....	tr.	....	tr.	....	....	....
Fine sand.....	1/4-1/8.....	.7	.1	.1	tr.	.1	....	tr.	....	....	....
Very fine sand.....	1/8-1/16.....	7.4	7.7	3.8	1.9	1.0	....	.2	.2	....	....
Coarse silt.....	1/16-1/32.....	36.8	30.6	27.1	21.3	12.0	.7	2.4	8.9	....	.8
Medium silt.....	1/32-1/64.....	35.0	44.8	42.7	60.5	46.0	5.3	13.8	17.8	28.5	8.5
Fine silt.....	1/64-1/128.....	14.0	14.5	19.4	14.0	30.8	36.4	44.2	29.1	57.0	36.1
Very fine silt.....	1/128-1/256.....	5.1	1.9	4.6	1.5	7.0	25.8	32.0	14.5	8.8	41.1
Coarse clay.....	1/256-1/512.....	.8	.4	1.6	.3	1.8	24.5	6.3	14.5	3.3	12.2
Medium clay.....	1/512-1/1024.....	.2	....	.4	.1	.2	6.6	.5	11.8	1.8	1.0
Fine clay.....	1/1024-1/2048.....	....	....	.1	....	....	1.0	....	2.2	.3	.1

TABLE 8.—*Mechanical Composition of alluvial Silts in small Streams.*

Names of ingredients.	Size of diameter in millimeters.					
		70	71	72	73	
Large boulders.....	256-128.....	....	....	....	....	
Medium boulders.....	128-64.....	....	....	....	....	
Small boulders.....	64-32.....	....	....	....	....	
Very small boulders.....	32-16.....	....	....	....	....	
Very coarse gravel.....	16-8.....	....	....	....	....	
Coarse gravel.....	8-4.....	....	....	....	....	
Medium gravel.....	4-2.....	....	....	....	....	
Fine gravel.....	2-1.....	....	....	....	....	
Coarse sand.....	1-1/2.....	.2	....	....	tr.	
Medium sand.....	1/2-1/4.....	.9	....	.2	tr.	
Fine sand.....	1/4-1/8.....	11.9	.9	.1	tr.	
Very fine sand.....	1/8-1/16.....	9.8	16.2	8.8	3.5	
Coarse silt.....	1/16-1/32.....	28.7	22.2	19.1	12.3	
Medium silt.....	1/32-1/64.....	40.6	36.8	35.3	19.4	
Fine silt.....	1/64-1/128.....	5.9	28.6	23.8	30.9	
Very fine silt.....	1/128-1/256.....	1.5	3.2	10.6	24.6	
Coarse clay.....	1/256-1/512.....	.2	.3	1.3	7.1	
Medium clay.....	1/512-1/1024.....	....	....	.1	.9	
Fine clay.....	1/1024-1/2048.....	....	....	....	.2	

TABLE 10.—*Mechanical Composition of Silt in large Streams*

Names of ingredients.	Size of diameter in millimeters.	101	102	103	104
Large boulders.....	256-128.....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....
Coarse gravel.....	8-4.....	....	....	2.1	....
Medium gravel.....	4-2.....	....	tr.	1.9	.3
Fine gravel.....	2-1.....	.3	.4	2.8	.2
Coarse sand.....	1-1/2.....	1.7	5.6	7.5	.4
Medium sand.....	1/2-1/4.....	2.6	5.8	4.3	.5
Fine sand.....	1/4-1/8.....	3.5	12.6	12.7	6.4
Very fine sand.....	1/8-1/16.....	29.8	27.6	13.7	20.3
Coarse silt.....	1/16-1/32.....	38.4	34.0	34.5	30.4
Medium silt.....	1/32-1/64.....	18.7	11.6	14.8	28.7
Fine silt.....	1/64-1/128.....	4.0	2.3	4.8	11.3
Very fine silt.....	1/128-1/256.....	.8	.3	.6	1.5
Coarse clay.....	1/256-1/512.....	.2	....	.1	.3
Medium clay.....	1/512-1/1024.....	....	....	....	....
Fine clay.....	1/1024-1/2048.....	....	....	....	....

TABLE 11.—*Mechanical Composition of Sand from Lake Beaches*

Names of ingredients.	Size of diameter in millimeters.	105	106	107	108	109	110
Large boulders.....	256-128.....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....	....	....
Coarse gravel.....	8-4.....	....	....	....	....	....	....
Medium gravel.....	4-2.....	.6	....	....	....	....	....
Fine gravel.....	2-1.....	1.0	1.5	.6	tr.	....	....
Coarse sand.....	1-1/2.....	37.8	27.2	15.8	10.6	5.0	3.2
Medium sand.....	1/2-1/4.....	35.2	61.8	37.9	41.4	30.0	27.9
Fine sand.....	1/4-1/8.....	25.3	9.5	45.7	47.8	65.0	68.8
Very fine sand.....	1/8-1/16.....	tr.	....	tr.	....	....	tr.
Coarse silt.....	1/16-1/32.....	....	....	....	....	....	....
Medium silt.....	1/32-1/64.....	....	....	....	....	....	....
Fine silt.....	1/64-1/128.....	....	....	....	....	....	....
Very fine silt.....	1/128-1/256.....	....	....	....	....	....	....
Coarse clay.....	1/256-1/512.....	....	....	....	....	....	....
Medium clay.....	1/512-1/1024.....	....	....	....	....	....	....
Fine clay.....	1/1024-1/2048.....	....	....	....	....	....	....

TABLE 12.—*Mechanical Composition of Lake Silts*

Names of ingredients.	Size of diameter in millimeters.			
		111	112	113
Large boulders.....	256-128.....	....	....	....
Medium boulders.....	128-64.....	....	....	....
Small boulders.....	64-32.....	....	....	....
Very small boulders.....	32-16.....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....
Coarse gravel.....	8-4.....	....	....	....
Medium gravel.....	4-2.....	tr.	.2	....
Fine gravel.....	2-1.....	.5	.8	....
Coarse sand.....	1-1/2.....	2.2	4.1	tr.
Medium sand.....	1/2-1/4.....	1.7	3.6	.1
Fine sand.....	1/4-1/8.....	4.0	5.4	.7
Very fine sand.....	1/8-1/16.....	11.1	12.8	10.4
Coarse silt.....	1/16-1/32.....	35.0	32.0	31.2
Medium silt.....	1/32-1/64.....	26.2	26.6	32.4
Fine silt.....	1/64-1/128.....	14.1	9.3	12.0
Very fine silt.....	1/128-1/256.....	4.2	4.0	7.2
Coarse clay.....	1/256-1/512.....	.7	.6	1.5
Medium clay.....	1/512-1/1024.....	.3	.1	3.1
Fine clay.....	1-1024-1/2048.....	....	....	1.0

TABLE 14.—*Mechanical Composition of Silts in Harbors*

Names of ingredients.	Size of diameter in millimeters.	121	122	123	124	125	126	127	128	129	130	131	132	133
Large boulders.....	256-128.....	...	...	...	...	...	...	...	...	...	...	...	...	...
Medium boulders.....	128-64.....	...	...	...	...	...	...	...	...	...	...	...	...	...
Small boulders.....	64-32.....	...	...	...	...	...	...	...	...	...	...	...	...	...
Very small boulders.....	32-16.....	...	...	...	...	...	...	...	...	...	...	...	...	...
Very coarse gravel.....	16-8.....	...	...	...	...	...	...	...	...	...	...	...	...	...
Coarse gravel.....	8-4.....	...	...	...	...	...	...	...	...	...	...	...	...	...
Medium gravel.....	4-2.....	.2	...	...	...	...	...	.2	...	...	.3	...	...	...
Fine gravel.....	2-1.....	.1	...	...	...	...	...	.2	.3	...	.2	...	tr.	...
Coarse sand.....	1-1/2.....	.5	.2	...	.4	.2	.2	.9	1.2	tr.	.7	tr.	.4	.2
Medium sand.....	1/2-1/4.....	.6	.4	.6	.2	.1	.3	.5	.7	tr.	.7	tr.	.5	.1
Fine sand.....	1/4-1/8.....	12.6	16.7	9.8	3.3	4.5	2.3	3.0	5.0	tr.	2.2	.4	.8	.2
Very fine sand.....	1/8-1/16.....	52.9	22.9	16.4	13.0	11.4	21.3	7.1	9.4	3.1	8.6	5.3	4.8	1.4
Coarse silt.....	1/16-1/32.....	24.2	21.1	33.1	45.1	45.6	30.6	19.5	15.6	12.4	17.2	13.2	13.2	9.7
Medium silt.....	1/32-1/64.....	6.8	12.7	27.4	27.4	28.5	30.6	37.8	35.7	37.2	20.6	28.2	26.4	27.9
Fine silt.....	1/64-1/128.....	1.7	14.6	10.5	8.0	8.3	10.2	23.2	15.6	24.6	26.5	31.1	34.8	39.0
Very fine silt.....	1/128-1/256.....	.2	8.3	2.1	1.9	1.3	3.3	5.8	10.0	9.6	14.1	11.7	12.0	15.3
Coarse clay.....	1/256-1/512.....	...	2.6	.5	.6	.1	.5	1.5	4.7	3.5	7.6	6.4	6.0	5.5
Medium clay.....	1/512-1/1024.....	...	.4	.1	...	...	...	.2	1.2	.9	.8	2.4	.7	.7
Fine clay.....	1/1024-1/2048.....	...	...	...	...	...	...	...	.6	.2	.2	.8	.1	.1

TABLE 17.—*Mechanical Composition of Materials from the submerged west Slope of the west Coast of America*

[illegible]

TABLE 19.—*Mechanical Composition of Deposits in the Sea near Volcanoes*

Names of ingredients.	Size of diameter in millimeters.	176	177	178	179	180	181
Large boulders.....	256-128.....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	1.2	....	....	....	....
Coarse gravel.....	8-4.....	.2	.9	.8	....	....	....
Medium gravel.....	4-2.....	.5	2.0	2.0	1.4	1.7	....
Fine gravel.....	2-1.....	.8	7.6	3.8	2.7	2.4	....
Coarse sand.....	1-1/2.....	1.2	.9	10.0	3.5	1.2	....
Medium sand.....	1/2-1/4.....	1.7	4.1	25.3	1.8	1.7	1.0
Fine sand.....	1/4-1/8.....	75.6	71.4	54.8	23.2	13.2	6.2
Very fine sand.....	1/8-1/16.....	14.5	10.3	2.6	27.8	40.0	34.4
Coarse silt.....	1/16-1/32.....	4.8	1.3	.5	18.6	23.0	37.5
Medium silt.....	1/32-1/64.....	1.3	.1	....	15.3	13.0	14.7
Fine silt.....	1/64-1/128.....	.3	....	....	3.1	3.4	3.8
Very fine silt.....	1/128-1/256.....	....	....	....	1.5	.4	1.3
Coarse clay.....	1/256-1/512.....	....	....	....	.7	....	1.0
Medium clay.....	1/512-1/1024.....	....	....	....	.1	....	....
Fine clay.....	1/1024-1/2048.....	....	....	....	....	....	....

TABLE 20.—*Mechanical Composition of Materials from Deposits near the Margins of Ocean Basins*

Names of ingredients.	Size of diameter in millimeters.	182	183	184	185	186	187	188	189	190
Large boulders.....	256-128.....	....	....	....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....	....	....	....	....	....
Coarse gravel.....	8-4.....	11.4	....	....	....	....	....	....	....	....
Medium gravel.....	4-2.....	53.0	....	16.5	....	....	....	....	....	....
Fine gravel.....	2-1.....	31.7	....	19.2	....	....	....	....	....	....
Coarse sand.....	1-1/2.....	3.8	....	5.2	....	....	....	.5	....	....
Medium sand.....	1/2-1/4.....	....	....	3.4	....	....	....	2.2	....	....
Fine sand.....	1/4-1/8.....	....	tr.	5.4	.3	tr.	.2	23.5	....	2.3
Very fine sand.....	1/8-1/16.....	....	80.0	32.2	37.7	26.0	13.2	14.0	7.1	2.0
Coarse silt.....	1/16-1/32.....	....	18.0	11.4	37.0	59.0	34.8	25.0	16.9	5.6
Medium silt.....	1/32-1/64.....	....	2.0	4.4	18.8	13.0	33.1	25.0	33.8	13.2
Fine silt.....	1/64-1/128.....	....	tr.	1.1	3.8	2.0	10.2	5.0	33.0	26.4
Very fine silt.....	1/128-1/256.....	....	....	.2	1.5	tr.	5.0	1.3	5.0	19.8
Coarse clay.....	1/256-1/512.....	....	....	.1	.9	tr.	1.8	1.2	2.1	17.8
Medium clay.....	1/512-1/1024.....	....	....	....	.4	....	1.0	....	1.6	10.0
Fine clay.....	1/1024-1/2048.....	....	....	....	....	....	.5	....	....	2.3

TABLE 23.—*Mechanical Composition of dune Sand.*[illegible]

TABLE 23.—*Mechanical Composition of dune Sand—(Continued)*

[illegible]

TABLE 24.—*Mechanical Composition of incipiently blown Sand*

Names of Ingredients.	Size of diameter in millimeters.	249	250	251	252	253
Large boulders.....	256-128.....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....	....
Coarse gravel.....	8-4.....	....	....	....	....	....
Medium gravel.....	4-2.....	....	....	....	....	....
Fine gravel.....	2-1.....	....	.1	....	....	....
Coarse sand.....	1-1/2.....	.3	5.7	.6	tr.	16.8
Medium sand.....	1/2-1/4.....	5.7	36.3	2.6	.3	29.6
Fine sand.....	1/4-1/8.....	60.3	53.5	50.2	97.0	51.4
Very fine sand.....	1/8-1/16.....	29.9	2.6	44.6	2.9	.8
Coarse dust.....	1/16-1/32.....	2.8	1.0	1.4	....	....
Medium dust.....	1/32-1/64.....	.5	....	.5	....	....
Fine dust.....	1/64-1/128.....	....	....	tr.	....	....
Very fine dust.....	1/128-1/256.....	....	....	....	....	....
Coarse clay.....	1/256-1/512.....	....	....	....	....	....
Medium clay.....	1/512-1/1024.....	....	....	....	....	....
Fine clay.....	1/1024-1/2048.....	....	....	....	....	....

TABLE 25.—*Mechanical Composition of lee Sands*

Names of ingredients.	Size of diameter in millimeters.	254	255	256	257	258	259	260	261	262	263
Large boulders.....	256-128.....	....	....	....	....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....	....	....	....	....	....	....
Coarse gravel.....	8-4.....	....	....	....	....	....	....	....	....	....	....
Medium gravel.....	4-2.....	....	....	....	....	....	....	....	....	....	....
Fine gravel.....	2-1.....	....	....	....	....	....	....	....	....	....	....
Coarse sand.....	1-1/2.....	2.1	.2	.3	....	3.2	.6	.7	....	....	....
Medium sand.....	1-1/4.....	16.5	4.6	1.5	1.1	18.7	3.3	1.3	4.2	2.6	1.9
Fine sand.....	1/4-1/8.....	72.0	60.0	72.3	62.0	71.2	69.3	14.4	55.6	58.5	51.8
Very fine sand.....	1/8-1/16.....	7.5	31.0	23.8	32.1	5.0	20.5	65.2	34.0	28.8	32.0
Coarse dust.....	1/16-1/32.....	....	.7	2.1	3.4	3.9	5.9	16.3	5.6	9.0	13.7
Medium dust.....	1/32-1/64.....	....	....	....	.6	....	.3	.8	.3	.4	.3
Fine dust.....	1/64-1/128.....	....	....	....	....	....	....	....	....	....	....
Very fine dust.....	1/128-1/256.....	....	....	....	....	....	....	....	....	....	....
Coarse clay.....	1/256-1/512.....	....	....	....	....	....	....	....	....	....	....
Medium clay.....	1/512-1/1024.....	....	....	....	....	....	....	....	....	....	....
Fine clay.....	1/1024-1/2048.....	....	....	....	....	....	....	....	....	....	....

TABLE 26.—*Mechanical Composition of miscellaneous Collections of Dust—(Continued)*

TABLE 27.—*Mechanical Composition of Dust collected by Apparatus from the Atmosphere—(Continued)*

[illegible]

"GUMBO"
TABLE 32.—*Mechanical Composition of "Gumbo" from Pottawattamie County, Iowa*

Names of ingredients.	Size of diameter in millimeters.	363	364	365	366	367	368	369	370	371
Large boulders.....	256-128.....	....	....	....	....	....	....	....	....	....
Medium boulders.....	128-64.....	....	....	....	....	....	....	....	....	....
Small boulders.....	64-32.....	....	....	....	....	....	....	....	....	....
Very small boulders.....	32-16.....	....	....	....	....	....	....	....	....	....
Very coarse gravel.....	16-8.....	....	....	....	....	....	....	....	....	....
Coarse gravel.....	8-4.....	.5	....	....	....	....	....	....	....	....
Medium gravel.....	4-2.....	.9	.1	....	....	....	....	....	....	....
Fine gravel.....	2-1.....	.9	.1	tr.	....	....	....	....	....	....
Coarse sand.....	1-1/2.....	3.3	.4	tr.	tr.	....	tr.	....	tr.	.1
Medium sand.....	1/2-1/4.....	2.7	.9	.4	.5	tr.	tr.	tr.	tr.	.2
Fine sand.....	1/4-1/8.....	8.3	3.2	1.0	3.5	.2	tr.	.1	.2	3.3
Very fine sand.....	1/8-1/16.....	6.5	8.3	7.5	5.0	2.5	20.6	4.0	5.6	14.9
Coarse silt or dust.....	1/16-1/32.....	52.9	53.3	56.7	45.4	59.0	47.3	62.5	52.5	54.2
Medium silt or dust.....	1/32-1/64.....	15.1	22.1	20.8	31.9	25.1	19.3	22.5	30.6	17.4
Fine silt or dust.....	1/64-1/128.....	5.0	9.9	9.0	8.9	8.8	9.1	8.0	6.4	6.5
Very fine silt or dust.....	1/128-1/256.....	1.4	1.3	1.8	2.5	2.5	1.5	1.1	2.0	1.5
Coarse clay.....	1/256-1/512.....	.9	.5	1.4	.7	.6	.5	.3	.8	.4
Medium clay.....	1/512-1/1024.....	1.0	.4	.4	1.2	1.2	1.3	.9	.8	.8
Fine clay.....	1/1024-1/2048.....	tr.	tr.	....	tr.	tr.	tr.	....	tr.	....

GENERAL DISCUSSION OF DATA

MODES OF SEDIMENTARY SORTING

On the basis of these analyses as well as on general principles, it seems correct to distinguish between two or three main modes of sedimentation⁶ in the atmosphere as well as in water. These modes may be called *drifting*, *silting*, and *washing*, when occurring in water; and respectively as *blowing*, *dusting*, and *winnowing*, when effected by the atmosphere.

By *drifting* I mean the sedimentation which is effected on the bottom under water by the lowest part of a current always running in the same direction, when this current is strong enough to move materials by its own impact. Drifting is going on in all streams. It is without doubt also taking place in many parts of the sea, as on the continental shelves, and even at considerable depths farther out in the sea, as in the northeast part of the Gulf of Mexico. Our knowledge of submarine currents is very limited.

The analogous transportation and sedimentation effected by the wind on the surface of the ground we may distinguish as *blowing* of coarser sediments, such as sand and gravel. Such work is general and effective in dry regions and also on many shores of the sea. It produces the sand dunes and the lag gravels. In the atmosphere the direction of the current is more variable, but the mode of work is identical with drifting in water. Sand grains are picked up short distances and fall down. There is usually also a drifting, progressive motion of the deposit in the direction of a prevailing wind.

Washing is a mode of sedimentation in water which likewise takes place as a result of an interaction between bottom current and drift on the bed of some river, lake, or sea. It differs from drifting in that it is effected not by a continuous current in a more or less constant direction, but by currents that are intermittent and alternating, going back and forth usually at a somewhat divergent angle and following the rhythm of waves produced by the wind or by the tide.⁷ The directions of the alternating currents are more or less constant for each locality. This is the prevailing mode of work on all shores, but it extends out to any depth in the sea that may be affected by rhythmic bottom currents caused by the tide. Concerning these we have very little knowledge. As tidal

⁶ It is understood that the term sedimentation is here used in its widest sense, implying the three processes of transportation, sorting, and deposition. The first two of these processes always accompany each other and always also accompany deposition.

⁷ G. K. Gilbert: Lake Bonneville. U. S. Geological Survey, Monograph I, p. 37 et seq.

currents continue for much longer periods than currents produced by wind waves, the work produced by tidal currents evidently somewhat more resembles drifting than does washing effected by waves raised by winds in water near shores. It is also evident that, owing to various compensations and interactions of tidal and other currents, there must exist in the sea all gradations between alternating currents, interrupted currents, and continuous currents.

In the atmosphere no process takes place that is quite comparable with the washing effected by shore waves. The atmosphere has no upper surface which intersects the slopes of the continents. But there are some winds which in their duration and alternation with each other somewhat resemble tidal currents in the sea. These are the diurnal winds on seacoasts and the cyclonic winds. The former of these are believed to be of minor significance for atmospheric sedimentation, and the latter are subject to so many irregularities and to such effective systematic influences from the planetary winds that the sum total of their work is more like drifting. In particular cases, as in dune regions on the coast, the wind may work in a manner somewhat like washing performed by wave currents in water. We might then call their sedimentary work *winnowing*. But this winnowing will in its effects probably be more like work performed by tidal waves than by shore waves.

Silting is sedimentation in water that results in the deposition of somewhat fine material, which is suspended in the entire body of water, or at least in some considerable part of a main body of water. The water is sufficiently agitated to keep in suspension a part, but not all, of the load it carries. A part is deposited. Compared with drifting and washing, silting is a slow process and takes place in quiet waters. To some extent, silting goes on, however, almost everywhere, even in more rapidly moving currents. It is the principal mode of sedimentation in lakes and seas away from shores. It is also a very important part of sedimentation effected by rivers during floods.

In the atmosphere a similar process of sedimentation is one of the most common occurrences. This is generally known not as silting, but as *dusting*. Dusting consists in the settling of fine material from a relatively deep and quiet body of the atmosphere. The material must be fine enough to have become dispersed in the atmosphere during strong winds, but too coarse to be held in effective suspension at times and in places of lesser movement of the air. The process is universal in its geographical distribution. In most places the resulting sediment is so small in amount that it never can accumulate on land of moderate relief where erosion is at all effective. But over wide and extensive plains

it accumulates on flat lands, where the rainfall is wholly absorbed by the vegetation, mold, and soil, and thus is ineffective as an agent of erosion.

The general recognition of these modes of work is not new. We find words in the common vernacular that designate them; but, so far as I know, no investigation has previously been made to ascertain accurately the variations in sorting of materials resulting from different modes of natural sedimentation—that is, the nature of the mixing of different sizes of clastic elements in different kinds of sedimentary deposits. The analyses made and here presented show certain general persistent features in the distribution of the quantities of materials of different coarseness in the different deposits produced by these different modes of sedimentation. This distribution is characteristic for the two or three modes of sedimentation and different also for the two media of sedimentation, and clearly indicate the general validity of the modal classifications given. It seems that the measurements made warrant the statement of some general laws which govern sedimentation in these respects.

LAW OF THE CHIEF INGREDIENT

1. In most sediments there is a mean size of clastic elements that is present in greater quantity than any other size.

The validity of this law is already evident from the fact that there must be for each locality where sedimentation takes place only one *prevailing* current in the medium of deposition. It is highly improbable that two currents, or two alternatively successive velocities of the same currents, should be so nicely adjusted with regard to strength, time limits, and supply of burden that they would deposit equal quantities of their sediments at the same point. The prevailing current deposits the greater part of the sediment.

If a current were perfectly uniform its sediment might consist of particles of the same size. The mass of a particle capable of being transported by any particular current varies as the sixth power of its velocity, the material of the particle always having the same specific gravity and the same form.⁸ But such uniformity in natural conditions is nowhere in existence. A more true conception of the natural conditions of sedimentation is that it is effected in each particular locality by an infinite number of currents, differing in direction as well as in velocity and all

⁸ In this paper these two qualities are regarded as uniform unless specially stated. Quartz, limestone, and feldspar have so nearly the same specific gravity that no appreciable differences in texture caused by differences in specific gravity are likely to appear in any of the measurements here made. The particles in silt and dust are always more angular than sand, and this may be a factor of some importance in sedimentary sorting, but in this study it has been neglected.

contributing more or less to the deposit. Where the range of variation is small the mechanical composition of the resulting sediment will be somewhat uniform, and where this range is considerable a deposit will be formed that is comparatively more heterogeneous. There will be also differences in sorting by the same system of currents or two identical systems of currents if such should exist. This is due to the fact that sorting is a progressive process, and that the material supplied to the currents is of variable composition.

LAW OF DECREASING ADMIXTURES

2. If we separate the mechanic elements in a sediment into a series of groups (grades) containing clastic elements, having diameters bearing a constant ratio to the diameters in their next group, we find that the mass in each group tends to have a fixed ratio to the mass of the other groups. Excepting some special conditions, this ratio is such that the mass of any group is smaller the more its clastic elements differ in size from those of the mean size.

This ratio may be called the *index of sorting*, because it is the expression of the degree of perfection to which the sorting out of elements carried and deposited by other than the prevailing currents has been effected.

The prevailing current is, as stated, really only a conception. The prevailing system of currents would be a more exact phrase. By the momentary reaction between each elastic unit and any constant current, the latter will be resolved, next the unit carried into an infinite number of somewhat slackened currents, and the capacity for transportation by these slackened currents may be greatly reduced. Among boulders rolled by coursing streams we almost always find sand and even silt. It is on account of this interaction between any current and its own load or deposits that no sorting can ever be perfect, even by what may appear to be a constant current.

The index of sorting is determined by two factors: by the ratio maintained by the specific gravities of the sediment and of the transporting medium and by the nature of the current and duration of its work.

The former of these factors is a physical constant; the latter is an exceedingly variable factor. Owing to the former factor, there is a general difference of texture in sediments of the atmosphere and sediments of water. It is evident that if the ratio of the specific gravities of water and quartz were 1:1, the largest boulders would be carried as far as the finest silt. Water-logged fragments of wood, such as sawdust, twigs, and logs, are left together on a beach. If sand were only slightly heavier than water, its sorting would be slow and less perfect. On the other

hand, magnetite sand is better sorted than quartz sand because the former has a comparatively high specific gravity.

This principle is made use of in the construction of ore separators, and the laws governing its application are well known. To illustrate its effect in natural sorting, fourteen analyses were made of seven samples of various sands, each consisting in part of quartz and in part of magnetite. These analyses show that the chief constituents and the admixtures when averaged for the two minerals are distributed relatively as below:

Table showing sorting in Water of clastic Elements of different specific Gravity

Names of grades.	Coarse admixtures.				Maximum.	Fine admixtures.			
	4	3	2	1		1	2	3	4
Quartz sand.....	1.7	2.7	8.5	26.5	41.1	15.8	2.5	.1	.....
Magnetite sand....	.....	.1	6.9	17.5	71.5	3.7	.1	.....	.....

The quartz is distributed through eight grades and the magnetite through only six. It is also found that the maximum of the quartz grains in each pair of analyses was from one to three grades farther toward the larger sizes than the maximum of the magnetite grains. The distance between the two maxima in the seven pairs of analyses averages near one and a half grades. (See Table 30.)

List of Samples of Magnetite-bearing Quartz Sand and Magnetite Sand in Table 30

- 338. Magnetite-bearing quartz sand from Viejo Canyon, Presidio County, Texas.
- 339. Magnetite-bearing quartz sand from the beach of Lake Michigan, near Evanston, Illinois.
- 340. Magnetite-bearing quartz sand from the bed of Tornillo Creek, Brewster County, Texas.
- 341. Magnetite-bearing quartz sand from the beach of Matagorda Bay, Olivia, Texas.
- 342. Magnetite-bearing quartz sand from the beach of Matagorda Bay, Olivia, Texas; second sample.
- 343. Magnetite-bearing quartz sand from the Limpia Canyon, Davis County, Texas.
- 344. Magnetite-bearing quartz sand from a canyon in the Chinati Mountains, Presidio County, Texas.
- 345. Magnetite sand in sample number 338.
- 346. Magnetite sand in sample number 339.
- 347. Magnetite sand in sample number 340.

- 348. Magnetite sand in sample number 341.
- 349. Magnetite sand in sample number 342.
- 350. Magnetite sand in sample number 343.
- 351. Magnetite sand in sample number 344.

LAW OF THE SORTING INDEX

With their complexity and variation in continuity, speed, duration, and mode of application, the currents in the same element may form sediments differing greatly in their ratio of sorting. Most eolian deposits are better sorted than most water deposits; but not a few beach sands are better sorted than many dune sands. The condition producing the perfect sorting of beach sands is the prolonged continuation of repeated currents of subequal speed washing the deposit, as already explained. To account for every variation of sorting existing in nature is impossible, owing to the complexity of the factors involved; but it is quite practicable to differentiate one or two variations of sorting, due to some conditions of work that have general prevalence in the atmosphere as well as in water.

3. If the series of group separations are so placed that any group will contain clastic elements having diameters averaging half the length of the next coarser group and twice the length of the next finer group, then the index of sorting for aqueous sediments produced by drifting and silting is near 2.5:1, and for eolian sediments produced by the analogous modes of blowing and dusting it is near 4.5:1.

This is the most generalized statement that can be made for the mechanical composition of the two principal classes of sediments represented in the analyses made. The analyses used in obtaining the general averages of the contents of the grades of water deposits were those of 59 samples of known drifted materials and of 19 samples of presumably drifted materials, of 49 samples of known silted deposits and of 18 samples of presumably silted materials, namely:

Known drifted materials, numbers 9-21, 24-33, 35, 36, 56-69, 75-81, 84-89, 93-98, 100.

Presumably drifted materials, numbers 134, 137-141, 143, 145, 150, 155, 158, 171-173, 178-180, 184, 185.

Known silted materials, numbers 37, 46-55, 70-73, 101-104, 111-113, 121-133.

Presumably silted materials, numbers 151-154, 157, 159-164, 174, 175, 181, 187-190.

For eolian deposits the general averages were obtained from the contents of the grades in 73 samples of blown material and 74 samples of dust, including all analyses of this class of sediments.

As these materials are fairly representative for most conditions under

which any deposits are made, it is believed that the indices given will be found to be fair approximations of the mechanical composition of such sediments in general.

The ratios maintained by the percentages in all grades in the averages were found arithmetically between first the maximum and the average of the pair of admixtures of the first order, then between the average of this pair and that of the pair of admixtures of the second order, and so on. The sorting index was then obtained by averaging these ratios.

LAW OF THE SECONDARY MAXIMUM

In drifting and blowing, the finest particles are carried away from the place of deposition of coarser materials. Momentary vertical currents prevent the finest material from settling. Particles of somewhat larger size are alternately lifted and let down; the smaller of these are carried in long leaps, the larger in shorter leaps. With increasing sizes a limit of elements is reached that will not allow them to be lifted even momentarily. In the case of a material where all elements would have nearly equal size, and where the current would be too weak to momentarily move any of them, there could be no transportation; but if the same current were to attack a bed of more heterogeneous composition, the smaller grains would soon be partly removed from around the larger. These would then project up into the current. These larger elements, say pebbles, might still be too heavy to be lifted up momentarily at any time. The impinging current might nevertheless be strong enough to roll them on the surface of the other material. Working in this manner, the transporting power of the medium varies more nearly in approximation to its erosive force than to its transporting power. With changes in velocity the latter varies as the sixth power, while the former varies as the square. With variations in the speed of a drifting current it happens, therefore, much more frequently that coarser elements are rolled along on a supporting bed than that finer drifting material is lifted up and carried away with still finer elements. With increase of size of the clastic elements of the load, the transporting medium much more rapidly ceases to pick up elements near, but exceeding, the sizes it has the power to carry by momentarily lifting them than it ceases to roll elements of considerably larger size.

The operation of this law is the cause of the occurrence again and again in the analyses made of a secondary maximum among the coarse admixtures. The decrease in the quantities of the grades in the direction of the coarsest material is not continuous in such sediments; but there is a rise mostly in the fourth, fifth, and sixth grade of the coarse admixtures in drifted sediments and in the second, third, and fourth

grades in blown material. The average position of the culmination, or the highest point of this secondary maximum, is in the fourth grade of coarse admixtures for water drift and in the third grade for blown material. In other words,

4. When a transporting medium is supplied with sufficiently heterogeneous material it will tend to carry and to deposit more of two certain sizes of material than of any other sizes. The principal deposit it makes will consist of materials it can momentarily lift. With this it will leave an excess of another considerably coarser ingredient which it can roll, smaller in quantity. This makes what we may call a secondary maximum. For water deposits, the secondary maximum will consist of elements having a diameter about sixteen times the diameter of the elements in the chief ingredient. For wind deposits, the secondary maximum will consist of elements having a diameter about eight times that of the elements in the chief ingredient. In atmospheric sediments the quantities present in the secondary maxima usually average greater than in aqueous sediments, presumably because there is apt to be a greater supply of smaller clastic elements than of larger.

The facts on which the above inferences are based are not as full as would be desirable, but they are believed to be sufficient to sustain the statements made. It is believed that the relatively smaller distance between the secondary and primary maxima in blown sand than in drifted and washed sand will prove to be a diagnostic feature in the identification of blown sand which otherwise may resemble washed sand.

In the following table 23 samples of what appear to be true cases illustrating the operation of this law in sedimentation in water are averaged. All maxima believed to consist of the principal material laid down by the drifting current are averaged in one grade and the admixtures are then averaged in successive order for each grade. These averages are of the samples numbered 10, 11, 12, 13, 17, 18, 26, 35, 36, 37, 60, 69, 82, 86, 87, 89, 93, 96, 97, 100, 102, 103, 104. Of atmospheric sediments having secondary maxima clearly produced under similar conditions there are only seven: numbers 192, 194, 195, 196, 197, 211, and 218. In the table these are averaged in the same manner as the water sediments.

Table showing the Position and Height of the secondary Maximum in Water and Wind Deposits

	Coarse admixtures.							Maxi- mum.	Fine admixtures.				
	7	6	5	4	3	2	1		1	2	3	4	5
Water deposits....	.2	1.1	3.8	5.3	5.2	11.0	17.5	40.0	11.3	3.4	.7	.2	.1
Wind deposits.....	...	....	.3	10.0	19.5	12.8	17.4	33.7	5.3	.6	...	...	...

DIFFERENCES IN SEDIMENTS DUE TO DIFFERENT MODES OF WORK

Washed sediments.—As already stated, washing is an aqueous mode of sedimentation which has no analogue in the work performed by the atmosphere. In a separate average of 50 samples of beach materials it is found that nearly 66 per cent of the samples are contained in their maxima, and percentages equal to or exceeding 0.1 per cent are scattered through nine grades. The sorting index averages 4.5:1, the same as for atmospheric sediments. A curve drawn to show the quantities in the chief ingredient and the admixtures in this average coincides very closely with a similar curve drawn for blown material. The 50 samples of averaged washed materials were numbers 22, 23, 34, 38-45, 82, 83, 90-92, 99, 105-110, 114-120, 135, 136, 142, 144, 146-149, 156, 165-170, 176, 177, 182, 183, and 186.

It does not seem likely that such deposits as these could be recognized from their sorting as water deposits. Only one or two samples show a decided aqueous characteristic and these are numbers 177 and 176. The former has two secondary maxima, one of which occurs in the sixth grade from the maximum. Blown sand with its bulk as well sorted as this sample would be very unlikely to also contain as much as this of coarse material. The same may be said of sample 176.

Table showing Averages of the Maximum and Admixtures in Fifty Samples of Washed Materials

Coarse admixtures.				Maximum.	Fine admixtures.			
4	3	2	1		1	2	3	4
.1	.3	2.8	17.0	65.9	11.6	1.9	.2	.1

Drift and blown material, silt, and dust.—The difference between deposits formed by drifting and blowing on the one hand and by silting and dusting on the other is most evident in the general difference in the size of the elements in the chief ingredient. The two modes of transportation and sedimentation (drifting and silting in water and blowing and dusting in the atmosphere) overlap, of course, in each medium, with different speed of currents. A very fine sand may drift in a slow current of water and may be carried as silt in a fast current. It may be blown by a moderate wind and be lifted high, like dust, in a strong wind. The two modes change, one into the other, through imperceptible gradations. They are, as already stated, merely the opposite extremes of the

same process, differing only in this, that in drifting and blowing the material is not lifted far from the ground or from the bottom. In silt-ing and dusting the transported load is raised high up in the water or in the air, and there is less opportunity for elements of extremely different sizes to be swept along and become mingled with the sizes normal to the deposits of each prevailing current. From averages of the analyses in the two groups of the two transporting media it appears that the chief ingredient in drifted materials has higher percentage than in silt, and that in blown materials it has a higher percentage than in dust. At the same time drifted material has in most cases a greater range of grades than silt, and blown material has a greater range than dust. In silt as well as in dust the admixtures of the first order have higher percentages than in either drift or blown material. This difference is greatest in the wind deposits. Another difference is that in silt and dust the admixtures are almost always more symmetrically arranged on either side of the maximum than they are in blown or drifted material.

In drift this distribution is often extremely unsymmetrical. This irregularity in sorting of sediments carried in the lowest strata of each medium is due to a greater variation in velocities in the lower part of the medium than at greater heights.

Table showing Averages of Quantities in the Grades for Deposits resulting from each Mode of Deposition in Water and Wind Sediments

Materials averaged.	Coarse admixtures.						Maxi- mum.	Fine admixtures.						
	6	5	4	3	2	1		1	2	3	4	5	6	7
Drift (78 samples).....	.1	1.0	1.7	2.1	6.0	15.2	43.2	16.6	7.8	2.8	1.8	.8	.2	.1
Blown materials (73 samples).....	...	...	2.1	2.4	4.0	17.2	59.2	13.5	3.2	.8	.1	...	...	...
Silt (53 samples).....	.1	.3	.9	1.7	6.4	19.3	38.3	20.9	7.5	2.5	.7	.1	...	...
Dust (74 samples).....	...	.1	.2	.7	4.8	23.0	46.3	20.3	3.4	.2	...	...	...	...

Another observation that seems pertinent is that in drift and blown sand the coarse admixtures are in excess of the fine, while in silt and dust there is apparently an excess in the fine admixtures. The excess of the coarse admixtures in drift and blown sand is probably due to "rolling," as explained elsewhere, in connection with the discussion of secondary maxima. The excess of the fine admixtures in silt and dust may be caused by flocculation. These differences do not appear so clearly in the general averages. It is believed that the mingling of a number of acci-

dental ingredients operates to conceal them. If we select and examine deposits made under the most uniform conditions, these show better the features mentioned. The averages of four samples of sand obtained from single layers in dunes show such an excess in the coarse admixtures, and 27 samples taken from single layers of drift do the same; also nine samples of dust collected under conditions of small range of wind velocity and seven samples secured from single layers in glacial silt in each case show an excess of fine admixtures. Sand collected in the lee of high dunes nearly always has a considerable excess in the fine ingredients. Overloading and rapid sedimentation no doubt favor flocculation.

DIFFERENCES BETWEEN WATER AND WIND SEDIMENTS

General discussion.—The general differences in mechanical composition between water and wind deposits are clearly shown in several ways by the analyses presented. The total range of size of clastic elements in water deposits here examined is from boulders measuring 128 millimeters in diameter to clay particles measuring $1/2048$ of a millimeter. In the wind deposits the coarsest ingredient observed was 16 millimeters in diameter, and dust particles less than $1/256$ millimeter in diameter were practically absent. Sedimentation by the atmosphere, generally, is limited to a smaller range of sizes in both directions—that is, sedimentation resulting in appreciable deposits.

Difference in grade distribution.—The same is true if we consider the range of effective working limits of any particular local current. The range in this case can be more definitely given. The best characterization to be made for this limitation is expressed by the averages of quantities in all grades. For a general comparison we take averages, as before, by superimposing all the maxima on each other and all the admixtures of the same order on both sides in the greatest number of analyses available of sediments made by each medium. Such averages for both water and wind deposits are shown in the following table:

Average Mechanical Composition of 190 Samples of Water Deposits and of 147 Samples of Wind Deposits

Names of grades.	Coarse admixtures.							Maximum.	Fine admixtures.								
	7	6	5	4	3	2	1		1	2	3	4	5	6	7	8	9
Water deposits.....	tr.	.1	.5	1.0	1.4	5.2	16.9	47.9	16.5	6.1	2.0	1.0	.4	.1	tr.	tr.	tr.
Wind deposits.....	....	....	tr.	.2	.9	4.4	20.3	53.1	16.9	3.3	.5	tr.	....	....	....	....	....

From this table we see that in water deposits the chances of finding boulders or pebbles having a diameter 4,096 times as large as the diameter of the smallest grain of sand or clay in the same deposit are about equal to finding in a wind deposit pebbles or sand grains which have a diameter 256 times the diameter of the finest dust grain in the same deposit. We also note that the chief ingredient in water deposits contains about 5 per cent less than it usually does in wind deposits. The admixtures of the first order contain about 2 per cent less in water sediments than in wind sediments. In all the other admixtures the percentages are higher in water deposits, grade for grade, than in wind sediments.

Difference in the coarseness of the chief ingredient.—If we examine the coarseness of elastic elements present in the maxima of different samples, we find that the range in wind deposits is through eight grades and of water deposits is through 13. In tabular arrangement we find the distribution of maxima as below. In their chief ingredient some water deposits are coarser and some finer than any wind deposit.

Table showing the Number of Maxima in different Grades in all Sediments examined

Diameter in millimeters.	Wind sediments.	Water sediments.
32-16.....	..	3
16-8.....	..	6
8-4.....	..	17
4-2.....	..	4
2-1.....	4	5
1-1/2.....	4	24
1/2-1/4.....	11	10
1/4-1/8.....	55	51
1/8-1/16.....	10 ⁹	18
1/16-1/32.....	27	30
1/32-1/64.....	42	15
1/64-1/128.....	1	11
1/128-1/256.....	..	1

⁹ The small number of samples of wind sediments that have grains from one-eighth to one-sixteenth millimeter in diameter in their maxima shows that more collections would be desirable. Six of the ten samples of this material were collected from railroad coaches and from houses; one is volcanic dust, one was taken near a wagon road, and one came from a plowed field. Deposits of the fineness of these samples do not drift as dunes, but in dry and semi-desert regions they drift extensively and form flat stretches of land in the lee of dune regions and over many high plains. I have made other observations which convince me that if dust were collected on the western plains and plateaus in the same manner as I collected it in Illinois, the gap in the above table would be filled.

Difference in the quantity of the chief ingredient.—The difference is likewise evident from the variations in the percentages of the quantities contained in the chief ingredient. In the water deposits the percentages of the maximum range from 18.5 to 94.0 per cent, while in wind deposits there is a range from 25.1 to 97.0 per cent. These figures are not diagnostic. But if we arrange the maximum percentages of water deposits in groups, each ranging between limits of 10 units of per cent, we find evidence of the two different modes of sorting, one (drifting) resulting in producing maxima containing about 40 per cent of the sample and another mode (washing) sorting the sediments until about 65 or 70 per cent will be of one and the same grade. The two groups evidently overlap, as we would expect. Drifting under some conditions produces deposits which are better sorted than the least thoroughly sorted deposits produced by washing, as stated before.

Table showing Variations in the Percentages contained in the Maxima of all Sediments examined

Limits of groups in per cent.....	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Numbers of water sediments.....	3	28	49	34	22	23	14	5	4
Numbers of wind sediments.....	....	3	18	53	32	23	14	3	2

The slightly greater frequency in water deposits of maxima containing from 61 to 70 per cent than of maxima containing from 51 to 60 per cent is caused by the samples of washed materials. No similar grouping is indicated for the wind sediments, where perfection of sorting in the coarser deposits is effected only by the processes analogous to drifting and silting.

Difference as to average number of grades.—Again, the less effective sorting power of water, except in case of washing, is evident when we examine the number of grades containing any certain minimum percentage of the whole sample. The difference is evident, whatever quantity be taken as a minimum, as appears from the following:

Table showing the average Number of Grades containing Minimum Percentages

Minimum percentage.....	Trace.	.1	1.	5.	10.
Water deposits.....	7.93	7.9	5.9	4.0	3.
Wind deposits.....	6.02	5.7	4.6	3.3	2.7
Differences.....	1.91	2.2	1.3	.7	.3

Difference in uniformity of composition.—The simplest and, in one sense, the clearest way of appreciating the difference between wind and water deposits is to see the analyses arranged side by side, showing the actual distribution of material of different grades in each sample. The general uniformity shown in the composition of the wind sediments, excepting the coarsest, which are of small importance geologically, shows that in many cases it should be possible to distinguish between these two classes of deposits in any formation on the basis of their mechanical composition when this has been determined for a sufficient number of samples.

RESTRICTIONS IN THE APPLICATION OF SOME CHARACTERISTICS

The sorting index for the 50 samples of washed water deposits given in the tables is 4.5:1, which is the same as found in eolian deposits. In the two best sorted samples of washed water deposits the index is 9.3:1, much higher than the average for washed water deposits. Most washed sands have a high index, as has already been seen. For classifying elastic rocks correctly the sorting index can evidently not be used indiscriminately. Individual samples of any sediment may represent an extreme in its class. Averages should be obtained from typical samples. In this way mechanical analyses will no doubt be found helpful in distinguishing between wind deposits, water drift, and silted deposits. Water drift, blown materials, and washed water deposits may all be well sorted, but the sorting of the former seldom approaches that of dune sand and very rarely that of the best sorted washed deposit. In silt and dust the index is much more constant for each and approximates more closely the figures given. But even here exceptional cases exist. In 11 samples of loess from Pottawattamie County, in Iowa, analyzed in 1900, I find that the sorting index averages 4.9:1 and varies only slightly.¹⁰

¹⁰ Geology of Pottawattamie County. Iowa Geological Survey, vol. xi, p. 257.

List of Loess Samples, Table 31

352. Light yellow loess, section 33, Boomer Township, Pottawattamie County, Iowa.
353. From the basal part of the loess, Council Bluffs, Iowa.
354. Twenty feet above the base of the loess, Council Bluffs, Iowa.
355. Forty feet above the base of the loess, Council Bluffs, Iowa.
356. Sixty feet above the base of the loess, Council Bluffs, Iowa.
357. Twenty feet below the top of the loess, Council Bluffs, Iowa.
358. Fifteen feet below the top of the loess, Council Bluffs, Iowa.
359. Eight feet below the top of the loess, Council Bluffs, Iowa.
360. Two feet below the top of the loess, Council Bluffs, Iowa.
361. Ten inches below the top of the loess, Council Bluffs, Iowa.
362. Top soil of the loess, Council Bluffs, Iowa.

ORIGIN OF OOLITES AND THE OOLITIC TEXTURE IN ROCKS¹

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(Presented before the Society December 31, 1913)

CONTENTS

	Page
Introduction and historical sketch.....	745
Historical review.....	747
Oolites from Great Salt Lake, Utah.....	752
Calcareous oolites from Cambrian and Ordovician beds of Pennsylvania..	757
Siliceous oolites of Pennsylvania.....	760
Bellefonte type of siliceous oolites.....	764
Clinton oolitic iron ore.....	768
Summary and conclusions.....	773
Bibliography.....	774
Explanation of plates.....	778

INTRODUCTION AND HISTORICAL SKETCH

The study of oolites and oolitic texture has no claim to novelty. This peculiar texture early attracted the attention of scientists, and the microscope was used to elucidate the minute structure of these rocks nearly two centuries before the petrographic microscope came to be recognized as a necessary adjunct of a petrographic laboratory. As early as 1664 Hooke described in his volume on "Micrography"³ an oolite under the name of "Kettering-stone." His description runs thus:

"This stone which is brought from Kettering in Northamptonshire, and digg'd out of a quarry, as I am inform'd, has a grain altogether admirable, nor have I ever seen or heard of any other stone that has the like. It is made up of an innumerable company of small bodies, not all of the same cize or shape, but for the most part, not much differing from a globular form, nor exceed they one another in diameter above three or four times; they appear

¹ Manuscript received by the Secretary of the Society December 31, 1913.

² Introduced by Florence Bascom.

³ Robert Hooke: Micrography, or some physiological descriptions of minute bodies made by magnifying glasses, with observations and inquiries thereupon. November 23, 1664. 1667.

to the eye, like the cob or ovary of a herring, or some smaller fishes, but for the most part, the particles seem somewhat less, and not so uniform. . . .

"Where these grains touch each other, they are so firmly united or settled together, that they seldom part without breaking a hole in one or th' other of them, such as *a, a, a, b, c, c, &c.* Some of which fractions, as *a, a, a, a,* where the touch has been but light, break no more than the outer crust, or first shell of the stone, which is of white color, a little dash'd with brownish yellow, and is very thin, like the shell of an egg; and I have seen some of those grains perfectly resemble some kind of eggs, both in color and shape: But where the union of the contiguous granules has been more firm, there the divulsion has made a greater chasm, as at *b, b, b,* in so much that I have observed some of them quite broken in two, as at *c, c, c,* which has discovered to me a further resemblance they have to eggs, they having the appearance of a white and yelk, by two differing substances that envelope and encompass each other" (loc. cit., page 93).

See plate 26, figure 1, for a reproduction of Hooke's figure.

Even at this early date the question of origin received attention, for Hooke continues:

"I must not here omit to take notice, that in this body there is not a vegetative faculty that should so contrive this structure for any peculiar use of vegetation or growth, whereas in other instances of vegetable porous bodies, there is an *anima*, or forma informans, that does contrive all the structure and mechanisms of the constituting body, to make them subservient and useful to the great Work or Function they are to perform" (ibid., page 95).

After this pioneer description and observation on oolitic rocks little attention was given to them until about half a century ago. As geological knowledge advanced and as geological observations were extended, it became known that oolitic rocks were abundant and wide-spread at many geological horizons. The name "oolite" was even used as a formation name in England for certain portions of the Jurassic system. The actual formation of oolites, or of structures differing from these only in size, and hence called pisolites, was observed in such surroundings as the Carlsbad springs, while the oolitic texture was found to be characteristic of rocks other than limestones, because it occurred in iron ores (both hematite and siderite) and in siliceous rocks.

As the importance of oolites and the oolitic texture became apparent, attention was directed to their origin, and from the very beginning two widely different views were advocated by various authors. As early as 1851 De La Beche remarked that in shallow bays or tidal seas in warm climates, where evaporation is rapid, the sea-water would lose a part of its carbonic acid and thereby be forced to deposit a portion of the calcium carbonate which it held in solution. He writes:⁴

⁴ Sir Henry T. De La Beche: The Geological Observer, pp. 122-123. London, 1851.

"This may be well seen where waters highly charged with bicarbonate of lime flow slowly into some nook or bay, on tropical coasts, and even in localities where the rise and fall of tide is small, as, for instance, around Jamaica. It is in such situations, under favorable conditions, that the little grains termed oolites, formed of concentric coatings of calcareous matter, may be sometimes observed to form. A slight to and fro motion, produced by gentle ripples of water, may occasionally be seen to keep the carbonate of lime depositing in movement and dividing into minute portions, so that instead of a continuous coating of calcareous matter upon any solid substance beneath, a multitude of these little grains is produced. As might readily be anticipated, a small fragment of shell and even a minute crystal of carbonate of lime is sufficient to form a nucleus for the concentric coatings of these oolitic grains."

In 1862 Ferdinand Cohn described the formation of the "sprudelstein," or pisolite, of the Carlsbad springs as due to the activity of algæ. Thus early in the study of oolites two very different theories were advanced to account for the origin of the oolite grains. The first considered them as simple chemical precipitates, accumulated layer by layer on nuclei kept in motion by agitated waters. This is perhaps the most widely accepted view even at the present time, although, as will be presently shown, it is not as simple in its application as it would at first seem to be. The second theory holds that the oolites are the products of organic activity, and that the carbonate of lime was separated from the water by the organism and deposited around some nucleus to which the organism adhered. The majority of authors have considered algæ as the active agents, although some have considered protozoa responsible for certain oolites.

HISTORICAL REVIEW

It is not the purpose of the present paper to review in detail all of the literature which has appeared on the subject of oolites, but rather to call attention to a few of the more important contributions and to point out, in as far as it is possible to do so, how these views have affected or failed to be recognized in the later discussions of the subject. A bibliography is appended which contains all of the important references to the literature on this subject which have come to the writer's attention during the preparation of this paper.

In 1872 Dana, while describing the formation of beach sands around coral reefs, noted the fact that these sands were very frequently oolitic. He says:⁵

"In most localities the rock is an oolite or oolitic limestone. The grains become coated by the agglutinated carbonate of lime, and each enlarges thus to

⁵ J. D. Dana: *Coral Islands*, 1872, p. 153 (edition of 1879).

a minute sphere—a spherical concretion; and the aggregation of these concretions makes the oolite. The grains are usually much smaller than the roe of most fishes." . . .

Further on he says:⁶

"Oolitic beds appear to be confined to the superficial formations of a reef, that is, to the beach and wind-drift accumulations. No example has come under the notice of the author of oolite constituting the foundation rock of a reef or island."

After these observations by Dana little attention was given to the subject by Americans until Wieland made known the abundance of siliceous oolites in the vicinity of State College, Pennsylvania. Several papers appeared describing these, and they will receive due consideration in connection with the discussion of siliceous oolites later.

In 1896 Hopkins prepared an extensive report on the oolitic limestones of Indiana, to which he added a chapter on the subject of "Oolites and oolitic limestone in general."⁷ The failure of the early American geologists to take notice of these structures, or, at least, to give prominence to their records if they made them, is clearly indicated by the following extracts from Hopkins' paper:

"The Americans have very little on the subject, as it (oolite) is not a widespread formation in this country, and regions where it does occur have not been studied very thoroughly" (loc. cit., page 397).

"The principal deposits of calcareous oolites in the United States are in the Lower Carboniferous limestones in the Mississippi Valley. So far as known to the writer, none of any note occur in this country in any other formation" (ibid., page 403).

During the last two decades more attention has been given to oolitic rocks, and their occurrence has been recorded in many places and at various horizons. It is now recognized that oolites form a considerable part of the Upper Cambrian and Lower Ordovician limestones wherever they occur in this country, and that they are characteristic of this horizon in other countries as well.⁸

The majority of the investigations on the origin and formation of oolites have been carried on in Germany and England. As early as 1888 Nicholson (loc. cit.), while working with thin sections of oolitic rock from the vicinity of Girvan, Scotland, discovered concentric wormlike

⁶ Ibid., p. 156.

⁷ Indiana Dept. of Geology and Natural Resources, 21st Ann. Rept., pp. 397-412.

⁸ E. Blackwelder: China. Carnegie Institution of Washington, Pub. 54, vol. 1, 1907, pp. 378-383.

Nicholson: Scotland. Geol. Mag., Dec. iii, vol. v, 1888, pp. 22-24.

structures which he considered organic and referred to the Rhizopoda under the generic name *Girvanella*. Later Wethered, working on the British Carboniferous and Jurassic oolites, discovered similar structures, and considered all of these oolites to be of organic origin.⁹

In 1892 Rothpletz studied the oolites now forming along the shore of Great Salt Lake, Utah. He found that oolites obtained below the surface of the water were coated with a bluish-green algal mass, and that when the oolites from the shore were dissolved in very dilute hydrochloric acid there remained granules which he recognized as dead and crumpled algal cells. Among the living algæ he recognized both *Glæocapsa* and *Glæothece*, and he concluded that these forms were instrumental in separating the calcium carbonate and building up the oolites. When he extended his observations to the oolites forming around the Red Sea, he was unable to find any living algæ cells on the oolites, but within the little spheres he often found wormlike, and often branching, tubules which had been filled with calcite. These he concluded were identical with the structures described by Wethered from the Paleozoic oolites, and he believed that they were produced by threadlike algæ. As a result of his investigations, Rothpletz concluded that the majority of marine calcareous oolites with zonal and radial structure were produced by microscopic algæ of very low rank, capable of secreting lime.¹⁰ These investigations have been widely quoted and accepted as conclusive by many later workers on oolites.

Another interesting suggestion as to the organic origin of oolites is that made by Seeley in a paper read before the Bath meeting of the British Association, in which he compared oolites to the inter-nodal grains of nullipores. These grains have a concentric and a radial structure very similar to that found in oolites.¹¹ But in spite of this, Seeley was inclined to believe that the great majority of the oolite grains were formed by direct chemical precipitation, probably formed by evaporation of sea-water at the surface. He thought that this took place about shell fragments, and that these continued to increase until they attained a certain size, when they would sink to the bottom. This, he thought, would account for the uniformity of size of the grains in any one stratum.

Even though these various arguments for an organic origin had been advanced from time to time, the general consensus of opinion at the beginning of the present decade seemed to be that calcareous oolites were direct chemical precipitates formed about foreign nuclei kept in motion

⁹ E. B. Wethered: The formation of oolite. Quart. Jour. Geol. Soc., vol. li, pp. 196-209.

¹⁰ A. Rothpletz: On the formation of oolites. Am. Geol., vol. x, pp. 279-282.

¹¹ H. G. Seeley: The oolitic texture in rocks. Brit. Assoc. Adv. Sci., Bath meeting, 1888, pp. 674-675.

by the water, the precipitation being due to one of the following causes: (1) Cooling and consequent supersaturation of the solution (for example, Carlsbad springs); (2) evaporation of water and consequent supersaturation; (3) loss of excess of carbonic acid necessary to hold the carbonate in solution due to agitation of the water, to heating of the water, or to some other cause.

In all of the papers thus far mentioned one fact seems to have been ignored which was clearly pointed out by Sorby as early as 1879, namely, that all recent oolites consist of calcium carbonate in the mineral form aragonite and not in the more common and stable form of calcite. Sorby further pointed out that the spherical forms in the *sprudelstein* of Carlsbad are not formed of radially arranged crystals of aragonite, with their long axes in the radial direction, as would be expected if they formed by the normal deposition of the minute crystals from solution, but that the longer negative axes of the crystals are in reality tangential to the little spheres. He explains this arrangement by saying that probably "the minute crystalline nuclei were mechanically accumulated round a center, something like the layers in a large rolled snowball."¹² The mineral form aragonite never arises from supersaturated solutions of calcium carbonate under the ordinary conditions of temperature and pressure which prevail in the sea and lake waters where oolites are forming. This might have been used as a very strong argument in favor of the organic origin of oolites because both plants and animals are able to separate calcium carbonate from sea-water in this mineral form.¹³ But, so far as the writer knows, this argument was never advanced.

Linck was the first to attack the origin of oolites from the experimental point of view and produce oolites artificially under conditions which probably very closely approach those which obtain in nature where these structures are forming.¹⁴ He found that in all recent occurrences of oolite which he was able to examine the grains consisted of aragonite, while in the older or "fossil" oolites they consisted of calcite. He therefore concluded that all oolites were first formed as aragonite and later changed to calcite, a suggestion previously made by Sorby.¹⁵

Linck therefore set to work to produce oolites artificially in the laboratory. By experimenting directly with sea-water and certain precipitating reagents, he found that he could produce oolites that agreed with natural oolites in every detail. Sodium carbonate and ammonium car-

¹² H. C. Sorby: Ann. address. Geol. Soc. London, 1879, p. 74.

¹³ See Sorby, loc. cit.; also W. Meigen: Centralb. f. Min. Geol. u. Pal., 1901, pp. 577-578.

¹⁴ G. Linck: Neues Jahrb. f. Min. Geol. u. Pal., BB. XVI, 1903, pp. 495-513.

¹⁵ Loc. cit., p. 75.

bonate proved to be the most effective precipitating agents, and these may, and often do, occur in sea-water and in other places where oolites are now forming. They result from the decay or decomposition of animal and plant tissue, and they are most common in warm climates, where life is abundant and decay rapid.¹⁶

He summarizes his results as follows:

1. The maximum solubility of CaCO_3 in sea-water is .0191.
2. If the limit of solubility of calcium carbonate in the sea-water is exceeded, the CaCO_3 will separate out, forming calcite in temperate climates, and aragonite in tropical climates if the temperature of the water is high; but spherical oolites are never formed by this process.
3. If the calcium sulphate of the sea-water is precipitated by sodium or ammonium carbonate it will come down as calcium carbonate in the form of aragonite in either warm or cold climates, and for the greater part in the form of spherical oolites.
4. From a solution of calcium bicarbonate free from other salts the calcium carbonate is precipitated in temperate climates as calcite; in tropical climates, if the temperature is favorable, mostly as aragonite.
5. From a solution of calcium sulphate free from other salts, the calcium will be precipitated by sodium or ammonium carbonate in the form of calcite under either warm (40°C.) or cold (18°C.) conditions.
6. This demonstrates that the solubility of aragonite is greater in a solution with little or no other salt than in a solution well supplied with other salts, and that it is greater in a cold than in a warm solution. Calcite is exactly the reverse. Consequently at the same temperature sea-water will dissolve more calcium carbonate than fresh water; but there are circumstances under which aragonite and calcite are soluble to the same degree, and consequently they can form at the same time.
7. Calcium carbonate and calcium sulphate are more easily soluble in sea-water than in pure water.

Linck concluded as a result of his investigations that the aragonite oolites now forming in the sea are the result of chemical reaction between the calcium sulphate of the sea-water and the sodium carbonate and ammonium carbonate generated by the decay of animal and plant tissue. Their formation in the warmer regions is not so much due to the greater abundance of organisms in those regions as to the more rapid decay of organic tissue under the warmer climatic conditions.

He considers the Carlsbad sprudelstein to be formed in the same way as the recent marine oolites and to differ in origin from these only in

¹⁶ J. Walther previously suggested that oolites were formed by the decay of organic tissue. *Abh. sächs. Ges. Wissensch.*, Bd. 14 and 16, 1888, 1891.

that it separates from a very hot spring water poorer in salt but richer in sodium carbonate than the sea-water. The numerous dolomitic oolites and iron oolites he considers secondary, derived from original aragonite oolites by reactions with solutions of magnesium carbonate or iron carbonate.

The experimental work of Linck on laboratory material has been corroborated by the recent researches of Drew and Vaughan on the formation of oolites in the calcareous deposits around Florida and the Bahamas. Drew has shown that denitrifying bacteria play an important part in bringing about the chemical conditions necessary for the precipitation of the calcium carbonate, and Vaughan has shown that in these chemically precipitated muds oolites develop, often forming after the muds are precipitated.¹⁷

Thus we see that oolites are either organic, produced by algæ, as advocated by Rothpletz, or chemically formed by precipitation, as suggested by Linck and observed by Vaughan, the precipitating reagents probably being sodium carbonate or ammonium carbonate.

In the remainder of this paper I shall attempt to show that in all American occurrences of oolite which I have been able to study the formation of the oolites can be explained by the latter process, and that I think it is the only process by which they are formed.

OOLITES FROM GREAT SALT LAKE, UTAH

It was long ago recognized by geologists of the United States Survey that oolitic sand is now forming in certain localities along the shore of the Great Salt Lake. Gilbert recorded this occurrence in his monograph on Lake Bonneville,¹⁸ and several other writers have described it either from studies in the field or from investigations of the oolites obtained there. As already noted, Rothpletz studied these oolites both in the field and in the laboratory. He found that three types of oolites occur—round spherical or oval grains about one-third of a millimeter in diameter; long cylindrical grains, generally about half a millimeter long and one-tenth millimeter in diameter, and larger irregular tuberculated forms several millimeters in diameter. These oolites had a radially fibrous and concentric structure, and when obtained beneath the water were coated with minute algæ, while the grains from the shore when dissolved in very dilute hydrochloric acid yielded the dead and crumpled cells of algæ.

¹⁷ T. Wayland Vaughan: Jour. Wash. Acad. Sci., vol. iii, pp. 302-304. Carnegie Inst. Wash., Pub. 133, pp. 173-177; also Year Book No. 10, pp. 149-154.

¹⁸ Lake Bonneville, Mon. I, U. S. Geological Survey, 1890, pp. 169, 252.

He concluded that these oolites were of algal origin, and that the oolites were built up within the membrane of the algal mass by the activity of the algæ, for he says: "The oolites of the Great Salt Lake are, therefore, indubitably the product of lime-secreting fission-algæ, and their formation is proceeding day by day."¹⁹ Sherzer has several times referred to these oolites and published very fine photographs of the complete grains²⁰ (see figure 3, plate 26). Rothpletz failed to find nuclei of foreign material in the oolites he studied, but their absence is not characteristic of all of the oolites forming around the lake, as is clearly shown in the descriptions of sections of these oolites about to be given.

When tested by Meigen's reaction,²¹ the oolites of the Great Salt Lake, and also those from Pyramid Lake, Nevada, are found to be composed of calcium carbonate in the mineral form aragonite, and hence agree with those forming at Carlsbad and in the open ocean. In the thin section on which the following description is based many of the oolites had nuclei of foreign material, generally fragments of minerals, sharp and angular in outline. The majority of these nuclei were clear and glassy, except for minute inclusions. On examination with polarized light and crossed nicols the majority of the grains proved to be sanidine, although a few were plagioclase feldspar, showing numerous twin lamellæ. A few oolites were seen with nuclei of brown hornblende. The majority of the oolites are spherical, although some are oval in section, and some are even oblong, as if they were lengthwise sections of original cylindrical grains with a length three or four times the shorter diameter.

Micromasurements of these oolites agree very closely with the measurements given by Rothpletz and Sherzer. The large oolite shown in figure 2, plate 26, is .58 mm. in diameter, although the great majority of the spherical oolites are between one-third and one-half millimeter in diameter. The nucleus of the large grain shown in the figure is .13 mm. in diameter, while the nucleus of the adjacent smaller grain is .17 mm. The largest observed oblong grain was .75 mm. in length by .25 mm. in width. In a few of the more irregular grains the nuclei occupy over one-half the diameter of the oolite. In one individual the nucleus was a long angular fragment of sanidine, with a length of .43 mm. and a width of .16 mm. The entire oolite surrounding this nucleus was only a little over half a millimeter in length and about one-third a millimeter in width.

¹⁹ Loc. cit., p. 280.

²⁰ Michigan Geol. and Biol. Surv., Pub. 2, Geol. Ser. 1, p. 37, pl. I, fig. B. Bull. Geol. Soc. Am., vol. 21, pl. 46, fig. 4.

²¹ W. Meigen: Centralb. f. Min., Geol., u. Pal., 1901, pp. 577-578.

The oolites are composed of radially arranged fibrous aragonite around these nuclei and give the characteristic dark cross between crossed nicols. Some of the individual oolites show a somewhat coarser fibrous structure extending throughout the greater part of their diameter. Outside of this and separated from it and from one another by distinct lines come one or two very narrow zones of much finer fibers, likewise radially arranged. Two such zones occur in the large oolite grain shown in the figure. These zones have been broken away at one or two points during the grinding of the section.

If, as Rothpletz claims, these oolites are formed by the organic activity of minute algæ, how can this very marked difference in the physical make-up of the oolite be explained? If the chemical origin of the grains be admitted, the changes in structure can very easily be explained by the changes in the solutions producing them, as will be shown hereafter. While studying the oolites from the Red Sea, Rothpletz observed certain tubular structures within the oolites which looked like vermiform, sometimes branching, canals. These he explained as formed by threadlike algæ which were not concerned in the formation of the oolite, but which became imprisoned in the oolite as it formed. Can not the presence of dead and crumpled cells of certain minute algæ within the oolites of Great Salt Lake be best explained in the same way, namely, as cells which had selected the oolite as a point of attachment and became imprisoned within it by the further accretion of aragonite by chemical precipitation?

It is well known that the waters of Great Salt Lake are concentrated solutions which vary both seasonally and periodically through wide limits. The sets of analyses collected by Clarke, from which the following are quoted, show this variation very clearly:

Analyses of various Waters

	C	A	F	G	H
Cl	41.04	55.29	55.25	55.11	53.72
SO ⁴	5.25	7.69	6.73	6.66	5.95
CO ³	14.28	.21	.....	.....	.....
Na	33.84	30.59	34.65	32.97	32.81
K	2.11	1.11	2.64	3.13	4.99
Ca	.25	1.20	.16	.17	.31
Mg	2.28	3.73	.57	1.96	2.22
Salinity per cent.....	.35	$\left\{ \begin{array}{l} 3.30- \\ 3.74 \end{array} \right\}$		27.72	22.99
				17.68	

C. Pyramid Lake, Nevada. Mean of four concordant analyses by Clarke. Bull. 491, U. S. Geological Survey, page 147.

A. Mean of 77 analyses of ocean water from many localities, collected by the *Challenger* expedition. Cited in Bull. 491, U. S. Geological Survey, page 113.

F. Great Salt Lake. Collected in 1904. Bull. 491, U. S. Geological Survey, page 144.

G. Great Salt Lake. Collected in October, 1907. Bull. 491, U. S. Geological Survey, page 144.

H. Great Salt Lake. Collected in February, 1910. Bull. 491, U. S. Geological Survey, page 144.

A comparison of F, G, and H with A for normal sea-water shows that in composition the total salts of Great Salt Lake vary in only minor details from those of the oceans. The most notable variations are in the higher percentages of sodium and potassium, lower percentages of calcium and magnesium, and the total lack of the CO_3 radicle. The degree of salinity, on the other hand, is not only very much greater but at the same time is very variable. There is a seasonal rise and fall in the salinity of the water, which changes with the change in the level of the lake, due to the seasonal variation in the relation between the supply from precipitation and inflow and the loss by the evaporation of the water. The seasonal variation in the height of the lake is from 15 to 18 inches, being highest in June and lowest in November. There is also a periodic variation extending through a cycle of years and amounting in all to about 13 feet of change. The water of the lake was at a low stage in 1850; from that date it continued to rise till 1873, when it reached a maximum in elevation and a minimum in salinity (13.79 per cent in 1877). From 1873 to 1906 the volume of the lake decreased and the salinity increased (27.72 per cent in 1904). Among all the analyses of this water collected by Clarke, only one records the presence of the CO_3 radicle, and that sample was taken in 1877, when the salinity was near the minimum.

These facts concerning the composition of the salts and the salinity of the water have a direct bearing on the problem of the formation of the oolites. Gilbert remarked that: "Despite the fact that calcium carbonate is precipitated on the shore in the form of an oolitic sand, none of the analysts have succeeded in finding it in the brine; and it is probable that the weighable calcium found in two of the samples exists in the form of sulphate."²² It is a well known fact that calcium carbonate is one of the important salts in the river waters tributary to Great Salt Lake;²³ but it is evidently all destroyed by double decomposition immediately on entering the lake, and the greater part is eventually precipitated in the form of oolitic sand. Moreover, Jordan River, entering the lake near where

²² Mon. I, U. S. Geological Survey, p. 252.

²³ See Bull. 491, U. S. Geological Survey, p. 145.

the oolites are now forming, carries most of its calcium in the form of sulphate. The great abundance of sodium salts in the lake, some of them even to the point of supersaturation during the winter months (mirabilite, or Glauber's salt, is precipitated in great quantity when the temperature goes below 20 degrees F.), and the fact that the calcium indicated in all the analyses of the Salt Lake salts is probably present as a sulphate make it very probable that the reaction here is similar to that observed by Linck in the laboratory experiments. The chemistry of the reaction is, however, greatly complicated by the extremely dilute condition of the calcium salts present and the great degree of concentration of the sodium salts, particularly sodium chloride and sodium sulphate.

A very much stronger argument for the formation of oolites, according to Linck's reaction, is to be found in Pyramid Lake. In this lake the salinity is only .35 per cent, and the composition of the salts differs widely from those of sea-water and those of Great Salt Lake, as can readily be seen by a glance at the table of analyses. Some of the sodium here present is evidently in the form of sodium carbonate. The only locality where oolite is forming in Pyramid Lake is near hot calcareous springs.²⁴ The lime carbonate of these hot springs is evidently at once precipitated by the sodium carbonate of the lake water and partly in the form of oolites.

As already stated, the place on the shore of Great Salt Lake where the oolites are forming is also near a source of supply, namely, the mouth of the Jordan River, whose annual tribute of lime can not be small, but this river carries the lime largely as the sulphate. An analysis made in 1900 showed that this river near its entrance into Great Salt Lake had a salinity of over 1 per cent, and of the contained salts calcium formed over 10¼ per cent, while only a trace of CO₂ was present.²⁵ Until irrigation became extensive along the banks of this river, a few decades ago, calcium sulphate was present in these waters in excess of all other salts. The effect of irrigation has been to greatly increase the sodium chloride of the river and consequently to lower the relative position of the calcium sulphate; but the important point is still to be noted that the Jordan River, which is generally admitted to be the source of supply of the lime for the oolites, carries that lime as the sulphate and not as the carbonate.

If the oolites of Great Salt Lake are forming as chemical precipitates, the seasonal variations in salinity would readily explain the zones of different texture in the oolites. On the other hand, if the oolites are formed by algæ, how is it possible to explain the fact that these are forming in

²⁴ G. K. Gilbert: *Mon. I, U. S. Geological Survey*, p. 169.

²⁵ *Bull. 491, U. S. Geological Survey*, p. 145.

Pyramid Lake at only one point, and that near a hot calcareous spring, while throughout the lake calcium carbonate, or some calcium salt, is present in amounts considerably above the percentage generally present in Great Salt Lake? It seems to the writer that the chemical precipitation theory is the only one which will explain the origin of oolites in a body of water like Great Salt Lake, where the salinity may be almost 28 per cent and the calcium content less than one-sixth of 1 per cent, and also in Pyramid Lake, where the salinity is about one-third of 1 per cent, and yet the necessary reagents for the precipitation of aragonite oolites are at hand. The association of algæ with the oolites in Great Salt Lake is perhaps not merely a fortuitous condition, but really a causal relation; but it is because they die and their organic tissue decays, thus forming sodium carbonate, that they aid in building the oolites rather than by any organic process of secreting lime while yet alive.

CALCAREOUS OOLITES FROM CAMBRIAN AND ORDOVICIAN BEDS OF PENNSYLVANIA

The occurrence of oolitic limestone in the Upper Cambrian and Lower Ordovician limestones of both eastern and central Pennsylvania was recorded by Rogers in his final report of the first geological survey of the State.²⁶ He also recorded its occurrence at the same horizon in Virginia and eastern Tennessee, and remarked that: "So wide a geographical range manifests a remarkable extension of that peculiar condition in the waters which gave rise to the oolitic structure."

The calcareous and dolomitic oolites on which the following descriptions are based came from Center County, Pennsylvania. The calcareous oolites came from a fossiliferous layer of Upper Cambrian limestone outcropping in a hill about one-half mile south of the Waddle station of the Bellefonte Central Railroad. The dolomitic oolites came from the upper part of the Beekmantown limestones, where they outcrop near Spring Creek, in Bellefonte, a few hundred yards south of the Central Railroad of Pennsylvania station. This bed contains numerous nodules of the oolite replaced by silica and will be mentioned again under siliceous oolite.

The oolitic layer in the Upper Cambrian is dark gray, almost black in color, and frequently stained with iron rust. On a weathered surface it is medium gray in color and the oolites show distinctly. The following analysis, made for the writer by W. A. Royce, of State College, gives its chemical composition. An analysis of the oolitic sand from Great Salt Lake is placed beside it for comparison:

²⁶ *Geology of Pennsylvania*, vol. 1, 1858, p. 238.

	A	B
SiO ₂	1.83	4.03
Al ₂ O ₃	.85	.20
Fe ₂ O ₃	.70	
CaO	54.03	51.33
MgO .....	.....	.72
K ₂ O, Na ₂ O .....	.....	.63
H ₂ O (110° C.)	.05	.83
H ₂ O .....	.....	
CO ₂	42.53	41.07
SiO ₃ .....	.....	.89
Organic .....	.....	.27
	99.99	99.97

A. Analysis of calcareous oolitic limestone from Waddle, Pennsylvania, by W. A. Royce, of State College.

B. Analysis of oolitic sand from Great Salt Lake, Utah, by T. M. Chatard. (From U. S. Geological Survey Bulletin No. 491, page 533.)

The oolites are somewhat variable in size, either spherical, oval, or rod-like. The oval grains are generally larger than the spherical grains; the spherical grains vary in diameter between .25 mm. and .75 mm., while the oval grains are frequently over 1.00 mm. in length and the rodlike grains as much as 2.00 mm. long.

When examined in thin-section no nuclei of foreign material can be seen. The majority of the grains have a comparatively coarse, radially arranged fibrous structure. Some, possibly one-fifth of those in the slide, have their center formed by a single large calcite crystal, generally with polysynthetic twinning prominently developed. The sizes of these central crystals show considerable variations. They are usually large, having a diameter equal to at least one-half the diameter of the oolite; in some cases the whole oolite seems to have been replaced by the calcite crystal, while in other instances only a narrow zone of radially arranged fibrous material is left near the outer edge of the oolite. Whenever the radial structure is retained the oolites show a distinct dark cross between crossed nicols (see plate 26, figures 5 and 6).

The oolitic layers of limestone are the only layers that are distinctly fossiliferous at this locality. Trilobites are the most abundant, but they are very fragmentary. The fragments are so numerous, however, that considerable difficulty was encountered in selecting a sample for the analysis, which was in all probability free from such fragments.

These oolites evidently formed where decaying organic matter was abundant, and this material must have produced ammonium carbonate in ample quantities to precipitate these oolites in the form of aragonite,

as suggested by Linck.²⁷ The oolites have since changed to the more stable mineral calcite. In doing so the majority have retained their original radial fibrous structure; but many have started to recrystallize about a single calcite crystal as a nucleus and have continued to enlarge this crystal until it occupies the greater part, or, in some grains, the whole of the space originally occupied by the oolite grain (see plate 26, figures 5 and 6).

The dolomitic oolites in the upper part of the Beekmantown beds²⁸ are not associated with fossils, but they occur near the top of a limestone and dolomite series nearly 5,000 feet thick, in which other oolitic beds and fossiliferous layers are found at various horizons. The writer has already suggested that this whole series can best be explained as an ancient "coral reef" (if that term can be so applied), built up by calcareous algæ.²⁹ If this is true, then the decaying tissue of these algæ would generate sodium carbonate for the precipitation of the oolites. At other horizons, where fossils are more abundant, ammonium carbonate was, no doubt, the precipitating agent.

The changes which these oolites have undergone since their formation have been very different from those which affected the calcareous oolites from the lower horizon. In ordinary light, under the microscope, the individual grains are indicated only by a faint line which marks the outer margin of the oolite. No nuclei are present, and there is neither fibrous nor concentric structure within the grains. Between crossed nicols the interiors of the oolites are seen to be made up of irregular allotriomorphic grains of dolomite, not differing in any way from the grains which fill the interspaces among the oolites. In most cases there is a more or less complete ring of little rhombic crystals of dolomite lying close to the line which marks the margin of each oolite grain (see figure 3, plate 27). If it were not for these rings it would be impossible to recognize any trace of oolitic structure with the nicols crossed, and these rings are not prominent.

From a study of these dolomitic oolites alone it would be impossible to say whether the dolomitization had taken place contemporaneously with the formation of the rock or at a later date. But when the siliceous nodules are considered in connection with the associated dolomitic material, it at once becomes evident that dolomitization occurred after the

²⁷ See also Murray and Irvine: *Proc. Roy. Soc. Edinburgh*, vol. xvii, 1889, p. 89.

J. Walther: *Abh. sächs. Ges. Wissensch.*, Bd. 14 u. 16, 1888, 1891.

Clarke: *Bull.* 491, U. S. Geological Survey, 1911, p. 136.

²⁸ Bellefonte dolomite of Ulrich. *Bull. Geol. Soc. Am.*, vol. 22, 1911, p. 657.

²⁹ *Jour. Geol.*, vol. xxi, 1913, pp. 237-244.

rock had formed, and that only an incipient change had taken place when the replacement by silica was accomplished.

Plate 27, figure 1, illustrates a calcareous oolite from eastern Pennsylvania, which presents peculiar features that can not yet be explained.

SILICEOUS OOLITES OF PENNSYLVANIA

Siliceous oolites were first discovered in the vicinity of State College, Pennsylvania, and were described by d'Inwilliers in his report on Center County.³⁰ His description is as follows:

"Along the southeast side of the *Barrens*, in the vicinity of State College, is found a rock, so far as I know, peculiar to this locality. It has a general resemblance to *oolitic limestone*, but is composed of siliceous concretions, about the size of mustard seeds, imbedded in a siliceous matrix. Its color is usually white, though it is sometimes iron-stained. In other cases both concretions and matrix consist of *hornstone*. Large quantities of this material may be picked up from the surface in this region.

"I found fragments of this same material near the *Barrens* in Walker township, near Snyderstown."

About six years later Wieland became interested in these oolites and sent many samples to various institutions, both in this country and abroad. He also described in a short paper their geographical occurrence.³¹ Within the next few years three important papers appeared on these oolites. The first was by Barbour and Torrey, and included an illustrated description of the oolites and chemical analyses of different samples, showing that they graded from almost pure silica to very highly calcareous types. They concluded that the siliceous oolites were derived from the calcareous forms. They recorded the presence of organic remains as nuclei, but no such nuclei have been seen by any later investigators.³²

In 1892 W. Bergt published a very good description of these oolites, and pointed out the fact that silica does not now form by direct precipitation at the surface in grains similar to these. Spherulitic forms do occur in opal and chalcedony, but these can not be compared with the Pennsylvania oolite. He concluded that these oolites were secondary, due to the recrystallization of an original spherical grained opal or chalcedony.³³

The best microscopic description thus far published in this country is

³⁰ E. V. d'Inwilliers, Sec. Geol. Sur. Penna., vol. T4, 1884, p. 406.

³¹ Mineralogists' Monthly, Nov., 1890.

³² Am. Jour. Sci., 3d ser., vol. xi, 1890, pp. 246-249.

³³ W. Bergt: Gesellschaft Isis in Dresden, Abh. 15, 1892, pp. 115-124.

that by Hovey.³⁴ He evidently had only a few hand specimens of the material to work with and they were siliceous throughout. His conclusion in regard to the origin is stated thus:

"The rock was evidently made from clear quartz sand by the action of alkaline waters depositing silica in the form of chalcedony around the fragments or aggregates of fragments of quartz and making the cement between the spherules of the same substance, while some of the quartz grains were caught in the chalcedony without being made the nuclei of spherules" (loc. cit.).

In 1897 Wieland assigned the origin of these oolites to hot springs. He found associated with them peculiar chert boulders, which he considered to be the actual rims of hot springs and geysers on the shore of the sea where these accumulated. He thought that the silica first deposited would form rings, but that deposited while in more rapid motion would form the spherical oolites.

The following year a very good description, with illustrations, was prepared by J. S. Diller and published in Bulletin 150 of the United States Geological Survey. Diller called attention to the work of previous writers, but did not add anything new in the way of explaining the origin of these oolites.

This subject seems to have attracted no further attention until it was again brought before the geologists of this country in a paper by Moore, originally read before the British Association in 1911, and later published in the *Journal of Geology*.³⁵ In this he clearly demonstrated that when found in place these siliceous oolites were derived from original calcareous oolites. He described and figured microsections which showed various stages of gradation from complete calcareous oolites to wholly silicified grains. He thus substantiated the original explanation of Barbour and Torrey, that these were altered calcareous oolites.

A few months later another paper appeared by Ziegler, in which he describes what he calls several distinct types of siliceous oolites, and while he accepts Moore's explanation of the origin of one of the types (and this was the type investigated by all of the previous writers), he offers another explanation for the other types. He believes that many of these siliceous oolites were formed from pure quartz sands cemented and changed to siliceous oolite by silica-laden solutions subsequent to their deposition and after they were covered with limestones. But in order to account for the perfect concentric oolites he assumes that some of the sandstones already consisted of sand grains concentrically enlarged by

³⁴ E. O. Hovey: *Bull. Geol. Soc. Am.*, vol. 5, 1894, pp. 627-629.

³⁵ E. S. Moore: *Jour. Geol.*, vol. xx, 1912, pp. 259-269.

moving currents of siliceous waters (probably hot springs), and that subsequent to their deposition in layers the final cementing of the oolitic spherules took place. He summarizes his observations as follows:

"In conclusion, then, it may be said that siliceous oolite occurs predominantly in rocks of Upper Cambrian and Beekmantown age; that there is a series of definite layers, a conservative estimate being at least twenty; that some of the layers are the result of replacement of oolitic limestones, but that the majority are the result of direct deposition of silica from hot solutions about pure quartz sand."³⁶

The writer has spent a great deal of time studying these siliceous oolites, both in the field and in the laboratory. Most of the localities mentioned by Ziegler have been examined very carefully, and several other localities have been studied which are not mentioned in his or any other paper. The majority of writers have considered the occurrence of siliceous oolites a phenomenon confined to a limited area; but this is an erroneous idea, for they are not only wide-spread in their distribution in central Pennsylvania, but also occur among the calcareous oolites of the eastern part of the State in the more highly metamorphosed beds of the same horizon (see plate 27, figures 5 and 6).

The typical State College siliceous oolites have already been well described by both Hovey and Diller. The essential features are these: The oolites are generally almost spherical in shape and range in size from one to one and one-third millimeters in diameter. The majority of them show a clear quartz sand grain nucleus, but some only show granular quartz in the center. This does not, however, indicate that the oolites without a sand grain necessarily lack a nucleus. While some undoubtedly do lack nuclei, this fact has probably been exaggerated in the descriptions thus far published. The accompanying figure (figure 1) has been drawn to show how some of those grains which appear to lack a nucleus may really have one which has not happened to be cut by the plane of the section. It also serves to illustrate how the range in size assigned to these oolites is undoubtedly greater than it really should be. A double nucleus consisting of two sand grains within a single oolite can now and then be seen (plate 28, figure 2).

The quartz sand grain is very frequently enlarged by silica deposited in optical continuity with it. This secondary enlargement may consist of one or two zones, and when extensively developed may even show the outlines of a quartz crystal partially developed (plate 28, figure 3). As noted by Hovey, the first zone of secondary enlargement is always cloudy.

³⁶ V. Ziegler: *Am. Jour. Sci.*, 4 ser., vol. xxiv, 1912, pp. 113-127.

He assigned this cloudy appearance to impurities taken up by the sand grain in the process of the deposition of the silica about it. No form or composition of these impurities was mentioned. An examination with a very high power of the microscope, however, shows them to be minute, microscopic, rhombohedral crystals of calcite contained within the silica.

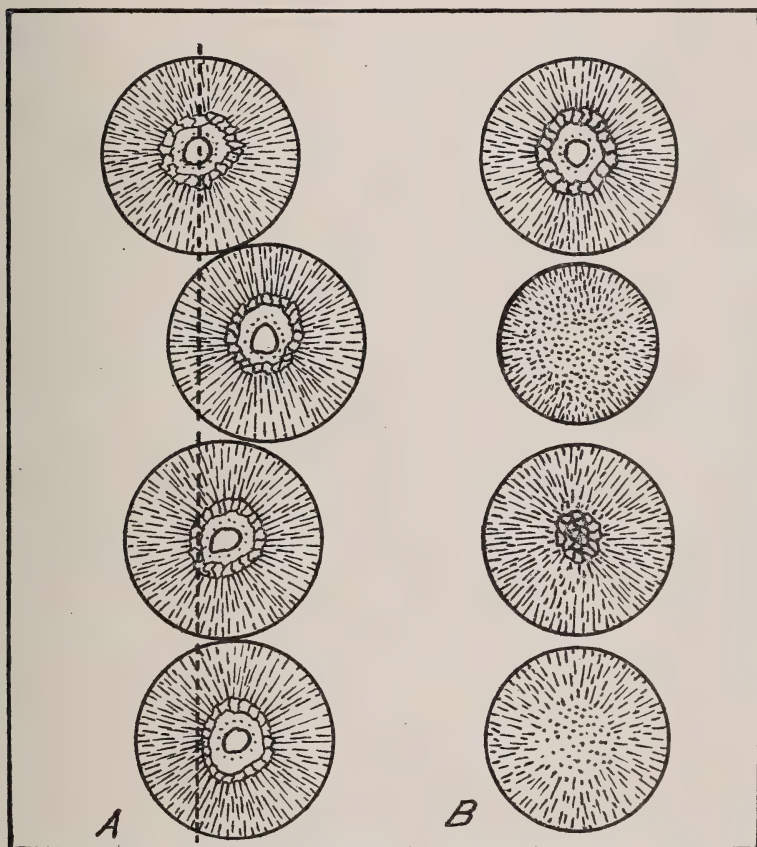


FIGURE 1.—*Diagrammatic Reproductions of oolitic Structure*

Showing how the four identical oolites of A, when cut by the plane of a section as indicated by the dotted line, may give rise to four apparently different types of oolites of somewhat different size. This probably explains the greater part of the apparent variation in the State College type of siliceous oolites.

The outer zone of secondary enlargement is always apparently clear, but may contain a few of these minute rhombohedral crystals of calcite.

Around the original or secondarily enlarged nucleus, and forming the greater part of the mass of the oolite, is siliceous material either in gran-

ular form or as finely fibrous zones of chalcedony. The granular material is quartz and forms a zone of varying width around the nucleus, or if there is no nucleus apparent it fills the center of the grain. This zone of granular quartz may fail completely and the fibrous chalcedony extend all the way to the nucleus, or it may make up practically the whole of the oolite.

In transmitted light the concentric rings of fibrous chalcedony frequently show faint yellow outlines, as if minute quantities of iron oxide had been deposited with the silica (plate 28, figure 1). "Occasionally the nucleal quartz is enveloped in a thick, dense layer of oxide of iron, and more rarely there are finely fibrous layers nearly midway between the center and the circumference of the spherule."³⁷

Outside of the oolites proper, but concentric with them, though forming a part of the matrix, occur incomplete bands of more coarsely fibrous or finely crystalline material. Under very high powers of the microscope these look like elongated columnar crystals of quartz, placed perpendicular to the surface of the oolites, with their free ends projecting into the interspaces, which are rarely incompletely filled. These bands are incomplete where the oolites approach each other closely. They evidently belong to the matrix surrounding the oolites, and the difference in size and texture of the component fibers indicates clearly that they developed at a different time and under somewhat different conditions from the fibrous material of the oolites proper. This fact has a direct bearing on the origin of the siliceous oolites.

Occasionally an oolite can be seen which has been fractured and the two parts moved slightly relative to one another. This crack or fracture has later been completely filled with crystalline quartz.

BELLEFONTE TYPE OF SILICEOUS OOLITES

In many of the beds of limestone and dolomite of the Beekmantown, or Lower Ordovician,³⁸ siliceous oolites occur, as noted by Ziegler, either in layers or as chert nodules. The State College type, with minor variations, is characteristic of the bedded layers wherever they occur, and they can be obtained at various outcrops from Krumerine, near State College, to Bellefonte, a distance of nearly 12 miles. As an example of the chert nodule type of siliceous oolite, the writer has selected such a nodule from

³⁷ Dillon: Loc. cit., p. 96.

³⁸ E. O. Ulrich: The Canadian of Ulrich, including, from the top down, the Bellefonte dolomite, Axeman limestone, Nittany dolomite, and Stonehenge limestone. Bull. Geol. Soc. Am., vol. 20, 1911, pp. 657-659.

the upper part of the Beekmantown (Bellefonte dolomite of Ulrich) for description.

This is from the same horizon and is an inclusion in the dolomitic oolite bed already described (see page 759). The oolites in this bed are very uniform in size and much smaller than those of the State College type. A series of measurements indicates that the range is between .45 mm. and .55 mm. in diameter. Probably the latter measurement is nearer the average, because the sections giving the smaller values may not have passed through the centers of the oolites. Neither the siliceous oolites nor the associated dolomitic forms have nuclei of sand grains, nor do they show any evidence of ever having had such nuclei. The majority of the siliceous spherules are aggregated into a single mass or nodule, but a few individual siliceous spherules occur completely surrounded by dolomitic grains and at some little distance from the general nodule. Small rhombic crystals occur within the majority of the siliceous oolites. When well within the oolite, these rhombic crystals show considerable variation in size and hold no definite position in the oolite, although they are generally near the center. Some of the siliceous oolites show one, or occasionally two, rings of these rhombic crystals near their outer margin. The oolite proper is wholly made up of cryptocrystalline quartz in component parts too small to be resolved by the microscope. These oolites, however, like those from the State College locality, are often enlarged by incomplete zones of definite quartz fibers radiating from their outer margins into the interspaces among the grains. These are clearly secondary, for they fail where the oolites were originally in contact. Some of the interspaces among the siliceous oolites are completely filled with quartz; others are still filled with crystalline dolomite. In the wholly dolomitic part of the specimen a zone of minute rhombic dolomite crystals, similar to those in the outer margin of the siliceous spherules, surrounds nearly every oolite (see plate 27, figure 3).

In a thin section cut from the boundary between the siliceous nodule and the adjacent dolomitic rock the oolites on either side of this boundary are seen to be identical in size and shape; they each have the zone of minute rhombic crystals of dolomite near the outer margin, and they differ only in that the siliceous oolites consist largely of fibrous quartz or chalcedony, while the others are made up of granular dolomite. These oolites were evidently derived from similar original spherules, and it is safe to assume that these originals consisted of calcium carbonate in the mineral form aragonite. They were evidently first attacked by magnesian waters which began to develop in the outer zones of these spherules, and sometimes deep within them, the minute rhombic crystals. Then

silica-bearing solutions began to act on certain particular areas and completely changed the unaltered oolites to fibrous quartz or chalcedony. The little rhombic crystals already formed were more resistant than the aragonite and were consequently unaffected. Later magnesian-bearing solutions once more affected the stratum and all of the material not previously altered was then changed to dolomite. The silica-bearing solutions did not stop when they completely altered the oolite grains within the nodule, but began to replace the matrix around and among the spheres. This matrix has in some interspaces been completely replaced, while in other spaces a part of the material was left and later changed to dolomite.

A comparable course of events led to the formation of the State College type of siliceous oolites. It differed from that outlined above in three respects: (1) no magnesian waters were involved in the process; (2) the oolites attacked by the silica-laden waters had in most cases nuclei of quartz sand grains; (3) the silica-bearing solutions frequently also contained iron. These differences caused the changes involved to take place as follows: The oolites composed of unstable aragonite began to gradually change to the more stable form calcite, just as in the organic accumulations around coral reefs at the present time a part of the aragonite quickly changes to calcite. This change frequently started near the foreign nucleus, but in many cases also near the outer margin of the oolites; it gave rise to the minute rhombic crystals which can still be seen under a high power of the microscope. Then silica-laden waters began to percolate through this oolite stratum. Because of the molecular influence or molecular affinity of the quartz sand grain nuclei, this silica in many oolites began to replace the aragonite near the nuclear sand grain and to secondarily enlarge that sand grain. The calcium carbonate which had already changed to calcite was more stable and it remained as minute rhombic crystals within the first zone of secondary enlargement, giving to it the dusty appearance which has already been noted. In many cases this secondary enlargement continued until it passed beyond the zone in which incipient calcite crystallization had taken place. In such cases the aragonite more distant from the nuclear sand grain was completely replaced, giving rise to the clear outer zone of secondary enlargement, and this zone frequently develops partial to more or less perfect crystal boundaries of quartz. The outer zones, for reasons which it is not easy to explain, are generally composed of granular or finely fibrous quartz or chalcedony. The interspaces, as in the previous case, are generally filled with somewhat coarser fibrous quartz, all of the fibers being placed perpendicular to the circumference of the original oolite when

they start from the outer margin of the oolite. The larger interspaces may be filled by irregular granules or fibers not related to the oolites.

In some instances the nuclei have not been secondarily enlarged, and then the fibrous quartz deposit has started to form at the very beginning of alteration. Apparently the fibrous material and the secondary enlargement have both been formed simultaneously in different grains from the same solution (plate 28, figure 3). These silica solutions seem to have carried iron also, and this has been deposited as the oxide in the fibrous zones together with the silica. In the slides studied by the present writer this occurred in only minute amounts, but Diller has observed cases in which it formed a thick dense layer around the nucleus.

The amount of iron present must have been very small, as is indicated by the following analyses, but it must have been deposited simultaneously with the quartz, and this throws an important light on the origin of ferruginous oolites, as will be explained later.

Analyses of siliceous Oolite from State College, Pennsylvania

	A	B	C
SiO ₂	95.83	98.72	98.26
SiO ₂	95.83	98.72	98.26
CaO	1.93	.09	.19
MgO	trace	.....	.....
K ₂ O, Na ₂ O .....	.....	.26	.28
Loss on ignition.....	.....	.34	.54
	100.69	99.95	99.89

- A. Barbour and Torrey: American Journal of Science, III, Volume XL, pages 246-249. These authors record a trace of MgO in this analysis. It is possible that the minute rhombic crystals in the cloudy zone of secondary enlargement may be dolomite.
- B. W. Bergt: Gesellschaft Isis in Dresden, Abhandlungen 15, pages 115-124.
- C. Ibid.

The source of the silica was undoubtedly sponge spicules and diatoms, one or both, or, perhaps, radiolarian skeletons, which were originally either in the same beds as the oolites or in beds adjacent to them.

The process of siliceous replacement was not a limited phenomenon, as indicated by many of the papers published on this subject, for these siliceous oolites occur not only over many square miles in the vicinity of State College and Bellefonte, but also in the eastern part of the State, in the oolitic beds of the same horizon—as, for example, near Allentown and north of Bethlehem. The chert boulders of the former (State College) vicinity are not limited in number to a few which might have

formed around hot springs, but are widely distributed at many horizons in this Lower Ordovician limestone. Chert bands and even bands of crystalline quartz resulting from the replacement of the original limestone and containing minute rhombic crystals similar to those within the oolites can be found. Where the limestones have been cracked and shattered during folding, quartz stringers and quartz veins can be found.

An almost exact parallel to the course of events here outlined for the silicification of these oolites has led to the preservation of fossils at a slightly higher horizon in a magnesian limestone bed which has been quarried near Henderson's Station, Montgomery County, Pennsylvania. The dynamic forces affecting these limestone beds have completely destroyed the fossils except where they have been preserved by silicification. In this case the fossils, *Maclurea* and *Raphistoma*, possessed a shell more resistant than the surrounding matrix. The silica-bearing solutions therefore attacked the matrix, removing that and depositing quartz about the fossil shells. This quartz gave rise to quartz crystals, with their long axes perpendicular to the surface of attachment, and they continued to grow until they filled the cavities within the shells, and when the shells were close together the interspaces among the adjacent shells also. This produces a result that is apparently exactly comparable to the filling of the interspaces among the oolites, except that in the former case the quartz crystals frequently attained a length of an eighth to a quarter of an inch, while in the latter they rarely attained the same fraction of a millimeter in length. In the original Henderson Station fossils the shells were evidently of calcite and more resistant than the matrix. They have, however, been removed by circulating waters and are now indicated only by the hollow molds within the quartz casing.

CLINTON OOLITIC IRON ORE

The Clinton oolitic iron ores are so widely distributed through the Eastern States from New York to Alabama and westward to Wisconsin and they occur within such narrow limits vertically in the geological column that they early attracted attention and have frequently been discussed. The Clinton ores are generally divided into two classes—the fossiliferous ores and the oolitic ores. The oolitic character is, however, the most constant feature and only the oolites are to be considered here. In describing the New York ores, Newland and Hartnagel say that one of the most characteristic features is "the almost universal presence of oolitic grains in the ores, even those which are apparently of purely fossiliferous nature."³⁹ Oolitic grains are almost always present in the

³⁹ N. Y. State Museum Bull. 123, p. 51.

Clinton ores of the Southern States, as is clearly indicated by the following statements. In describing the Clinton ores of the Birmingham district, Burchard says: "One of the two varieties of ore generally predominates in a bed, but in certain localities the fossil and oolitic materials are mixed in nearly equal proportions."⁴⁰ McCallie in describing the ores from Georgia says: "In some of the beds these particles make up the greater part of the ore, while in other beds they are almost entirely wanting."⁴¹

As the writer's field experience with these Clinton ores has been rather limited, the following description is based largely on thin sections and the published reports of those who have made a special study of this subject.

The Clinton oolites possess a concentric structure which is not always apparent in thin section under the microscope, but which can be readily seen if the individual spherules are separated from the matrix and tapped with a light hammer. Each spherule will break into a series of concentric shells. The material is so opaque that this concentric structure can not be seen under the microscope, but the nature of the nucleus is readily made out. This nucleus usually consists of a well rounded quartz sand grain, but it may be a fragment of a shell. According to McCallie, some of the spherules may have a central nucleus of oxide of iron surrounded by a layer of calcite or silica, which in turn may be inclosed in layers of oxide of iron. He furthermore reports that in nearly every section of these oolites from Georgia spherules can be found with a nucleus of a granular, green, or yellowish green mineral. In some cases this green mineral occurs as granules within the spherule even when they do not form the nucleus.

When the spherules are treated with hydrochloric acid, the iron oxide is dissolved out and there remains a skeleton of silica with a spongy and porous texture. This silica is often arranged in concentric layers which can be peeled off like the layers of an onion. This silica is amorphous.⁴²

These oolites of iron ore are very frequently associated with fragments of fossils which have been more or less completely replaced by the iron oxide. When these are treated with hydrochloric acid, they, too, leave behind a skeleton of silica, although this material can not be seen in microscopic sections.⁴³

This description is sufficient to indicate that the Clinton iron ore is made up in part of true oolites with concentric structure and generally

⁴⁰ Bull. 400, U. S. Geological Survey, p. 26.

⁴¹ Bull. 17, Geol. Survey Georgia, p. 168.

⁴² McCallie: Loc. cit., pp. 173-174.

⁴³ Smyth: Loc. cit., p. 489.

with nuclei of sand grains or some foreign material. These oolites are in almost every case mingled or associated with fossils or fragments of fossils composed of the same material, namely, iron oxide mingled with a certain amount of amorphous silica. Both oolites and fossils are, as a rule, imbedded in a matrix of calcium carbonate, sometimes in a granular condition and sometimes in the form of rhombohedral crystals. If these fossils and oolites were composed of calcium carbonate we would have an association exactly similar to that which is forming today around the Red Sea and certain deep-sea islands like the Bahamas and Bermudas, or like that which accumulated during the Pleistocene around the Florida Keys.

The fossils certainly were not originally formed of iron oxide and silica, and the oolites have just as certainly undergone the same changes and passed through the same history as the fossils. Evidently both were calcium carbonate originally, and they have been changed by silica-bearing ferruginous solutions and molecular replacement to the iron oxide and silica of which they are now composed. The process of replacement was exactly the same in general outline as that described for the replacement of the State College siliceous oolites. It differed from that process chiefly in that here ferruginous salts were dominant in the solutions, with silica playing a subordinate part, while in the siliceous oolite replacement silica was the dominant material in solution and ferruginous salts were present in an amount only sufficient to give a faint color to the concentric layers or occasionally form a coating around the nuclear sand grain.

Smyth and others have considered these Clinton oolitic ores direct chemical precipitates from ferruginous solutions, and they have based their argument on Newberry's statement that similar ores are now forming in many Swedish lakes.⁴⁴ The conditions under which these Swedish lake ores are accumulating are certainly far from comparable with those under which the Clinton ores accumulated; furthermore, the recent descriptions of these Swedish lake ores hardly suggest that they could ever become ores like those of the Clinton beds.⁴⁵

Smyth has undoubtedly presented the strongest arguments in favor of the original deposition of the iron ore as an oolitic iron oxide. Those arguments which have a direct bearing on the present discussion may be summarized as follows: (1) "How is it possible for an iron-bearing

⁴⁴ J. S. Newberry: *Genesis of the ores of iron*. *School of Mines Quarterly*, November, 1880.

⁴⁵ For descriptions of the Swedish lake ores see J. A. Philips and Henry Louis: *A treatise on ore deposits*, 1896, p. 538; also R. Beck: *The nature of ore deposits* (W. H. Weed), vol. 1, 1905, pp. 100-101.

solution to pass through this compact calcite (of the matrix) until the spherule is reached, and then begin to deposit the iron and replace the calcite?" (2) If the ore resulted from the alteration of a limestone, the alteration would begin at the outside of the spherules and work toward the center. After the outer layers were altered they must have served to protect the interior and some trace of the interior should be preserved. (3) If the ore was produced by substitution, it must have been precipitated first as iron carbonate, and if so it is difficult to account for its present composition.

These arguments against the replacement of original calcareous oolites may be answered categorically:

(1) If the original calcareous oolites were formed as such oolites are being formed today under all conditions, they were built of calcium carbonate in the mineral form aragonite, a mineral much less stable than calcite, and hence the first to be attacked by circulating solutions of any kind. These aragonite oolites would, therefore, most surely be replaced before any of the surrounding matrix was replaced by the ferruginous and silica-bearing solutions. Many fossils were originally composed of aragonite, and others which are not so constituted have the calcite of their skeletons in a more soluble form than the crystalline material which fills the interspaces among them. This is true of the fragments around a modern coral reef and was, undoubtedly, true in Clinton time. The fossil shells were, however, less easily affected than the aragonite spherules, and this is clearly indicated by the fact that in many of the fossil fragments the central interior part has not been replaced.

(2) The outer, earliest replaced zones do not form impervious cases, however dense they may appear under the microscope. Circulating solutions can penetrate these outer layers and alter the interior just as circulating solutions can enter a spherical agate, or a geode, and build up the interior after the outer shell or case has been completed. It is well known that fossils may be molecularly replaced by silica or other substances, such as pyrite, after they have been completely incased in a matrix. If the numerous fossils of the New Scotland beds of the Lower Devonian of eastern New York can be completely replaced by silica while they are incased in a matrix of limestone, or if the cephalopods of the Middle Devonian can be replaced by pyrite, is it not reasonable to argue that the silica-bearing ferruginous solutions could penetrate the granular crystalline calcite matrix of the Clinton oolites and fossils to bring about their replacement?

(3) It is clearly stated by those who have studied these ores most carefully, both in New York and in the more southern outcrops, that

some of the iron does occur as the carbonate. In Georgia, pyrite even is present to a certain extent. As already pointed out, McCallie records the fact that in the Georgia ores many of the spherules show green or yellowish green granules within them. These increase in numbers as the sections are taken from greater depths, and a diamond drill core from the Birmingham district at a depth of 800 feet from the surface reveals a large amount of this material (called glauconite by McCallie). This suggests that perhaps the reactions outlined by Cayeux for the European oolitic iron ores may all have taken place in the history of the formation of the Clinton ores. The possible replacements in passing from iron carbonate to the minerals now found in the ores are graphically summarized in figure 2. Calcium carbonate would first be changed to sider-

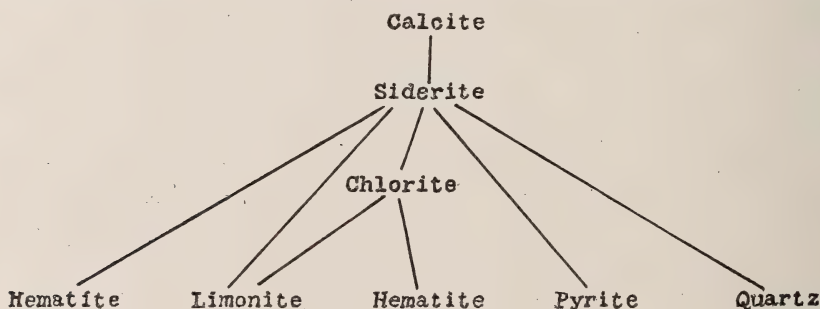


FIGURE 2.—Graphic Summary of mineralogic Changes in Ores

Modified from Cayeux. This shows the various mineral changes through which the aragonite oolites may have passed between their original condition and their present condition.

ite, and then this might give rise to any one of the minerals—red hematite, limonite, chlorite (Cayeux = glauconite of McCallie), pyrite, or quartz.

It is not within the field of the present paper to discuss the origin of the Clinton ores. The writer is convinced that all of the iron now found in the ore beds was probably deposited in them or near them in some form or other, but not as an oxide of oolitic texture. The iron oxide of the oolites is a secondary mineral exactly as the iron oxide of the fossils is a secondary mineral. Both fossils and oolites have been replaced by iron ore and silica which have come from some outside source; but it is believed that this source was within the beds where these ores are now found, and that the replacement was produced by slow movements of ground water. In the discussion of the siliceous oolites it was suggested that the silica probably came from diatoms and sponge spicules. The silica here might have been derived from the same source; but it seems

more likely that both the silica and the iron were originally deposited in these beds, as suggested by McCallie, in the form of glauconite. If this be true, the iron is secondary in respect to the oolites, but not necessarily secondary in respect to the Clinton beds, although in all probability some lateral movement has taken place during the interchange of materials and replacements of the oolites and fossils.

SUMMARY AND CONCLUSIONS

From the observations here recorded it seems evident, therefore, that the recent oolites now forming in Great Salt Lake and Pyramid Lake are like those now forming in hot springs and in the open ocean, composed of calcium carbonate in the mineral form aragonite, and they very frequently contain sand grains or nuclei of other foreign material. They probably are due to direct chemical precipitation caused by a reaction of sodium carbonate on the calcium sulphate held in solution by the water. The sodium carbonate in Great Salt Lake may be due to the decay of the dead minute algæ found so closely associated with these oolites below the limit of wave action. The argument in favor of these oolites having been derived from solutions of calcium sulphate is greatly strengthened by the fact that the great deposits of the oolitic sand along the shore of the lake are confined to a stretch near the mouth of the Jordan River, and this river until two or three decades ago carried calcium sulphate in solution in excess of any other salt. This salt is now exceeded in amount by sodium chloride, due to the effects of irrigation along the course of the river, but it is still the most prominent calcium salt.

The older oolitic beds of Pennsylvania were probably all originally laid down as beds of calcareous oolites composed of the mineral aragonite. This mineral, being unstable under ordinary rock-forming conditions, soon began to change. Where the beds were not affected by waters bearing other minerals in solution they simply changed to the more stable mineral calcite, and in doing so they often retained their original fibrous radiated and concentric structure. Sometimes, however, they became more or less completely changed into crystalline calcite, occasionally with twinned lamellæ.

When the circulating waters contained magnesium salts in solution the oolites became altered to dolomite, and in doing so lost their concentric and fibrous structure. The oolitic structure is then only shown by the faint outlines of the original oolites, sometimes accentuated by a ring of rhombohedral crystals around their margin, developed when the process of alteration first commenced.

When the circulating waters contained silica in solution the oolites were frequently replaced by silica. If the oolite had an original nucleus consisting of a quartz sand grain, this was frequently secondarily enlarged by the deposition of silica around it and in optical continuity with it. In other oolites the replacement was accomplished either by the deposition of granular quartz or of finely fibrous chalcedony. In any case minute rhombs of calcite are frequently inclosed in the replacing silica, showing clearly that the aragonite had in part changed to calcite before replacement by silica began. With the silica is often deposited minute quantities of iron oxide intimately mixed with the fibrous chalcedony.

At the Clinton horizon in the Silurian, in Pennsylvania, and in other States along the Appalachian mountain belt, occurs one or more beds of iron ore which are either fossiliferous or oolitic. Oolites are present to some extent in all of these ores. They were evidently formed originally as aragonite oolites and later changed, together with the associated fossils, by ferruginous solutions, into oolites composed of iron oxide and silica intimately mixed, but with the iron oxide greatly in excess.

It is very probable that the silica replacing the oolites of the Ordovician, and the iron and silica replacing the oolites of the Clinton, came from material already in the beds and at no great distance from where it now occurs. The silica probably came from sponge spicules and diatoms, and the iron (with its associated silica, perhaps) from green sand or glauconite.

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EXPLANATION OF PLATES

PLATE 26.—*Micro-sections of oolitic Structures*

FIGURE 1.—“Kettering Stone.”

Reduced from the plate in Hooke's Micrography, 1667. This rock occurs in the Jurassic oolite, near Kettering, Northamptonshire, England.

FIGURE 2.—Photomicrograph of sections of oolites from Great Salt Lake, Utah.

Nicols crossed. $\times 15$. The large grain near the center has a sanidine nucleus and shows the dark cross distinctly. The two outer zones of this grain differ in texture from the general mass of the grain.

FIGURE 3.—Great Salt Lake oolites.

Reflected light. After Sherzer.

FIGURE 4.—Section of Florida oolites from the Pleistocene.

Nicols crossed. $\times 15$. Many of the oolites have undergone a partial recrystallization.

FIGURE 5.—Section of Cambrian oolites from Waddle, Pennsylvania.

$\times 15$. Several of these have recrystallized into calcite grains showing twin lamellæ.

FIGURE 6.—Another section of Cambrian oolites from Waddle.

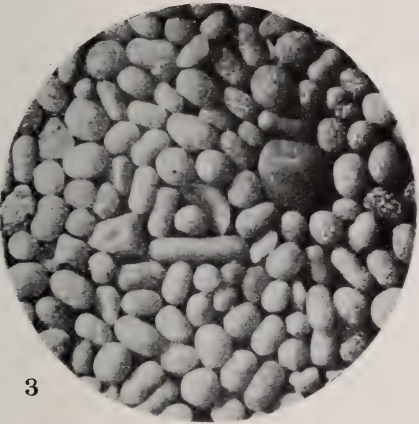
Nicols crossed. $\times 15$. The dark crosses show that the radial structure has been retained.



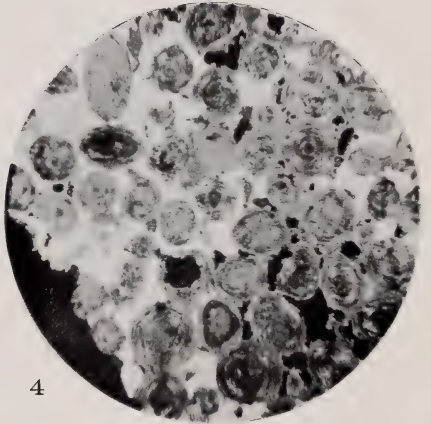
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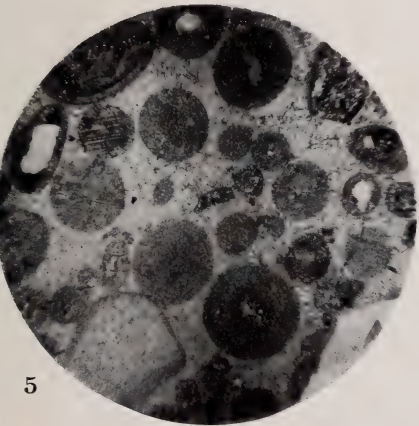
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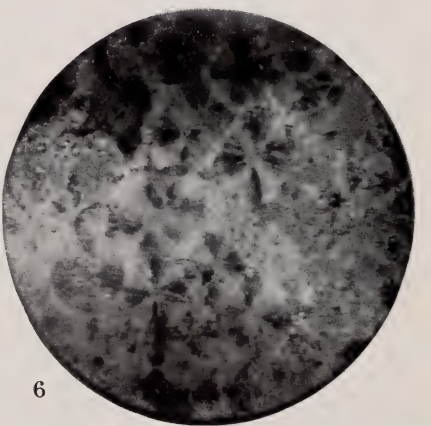
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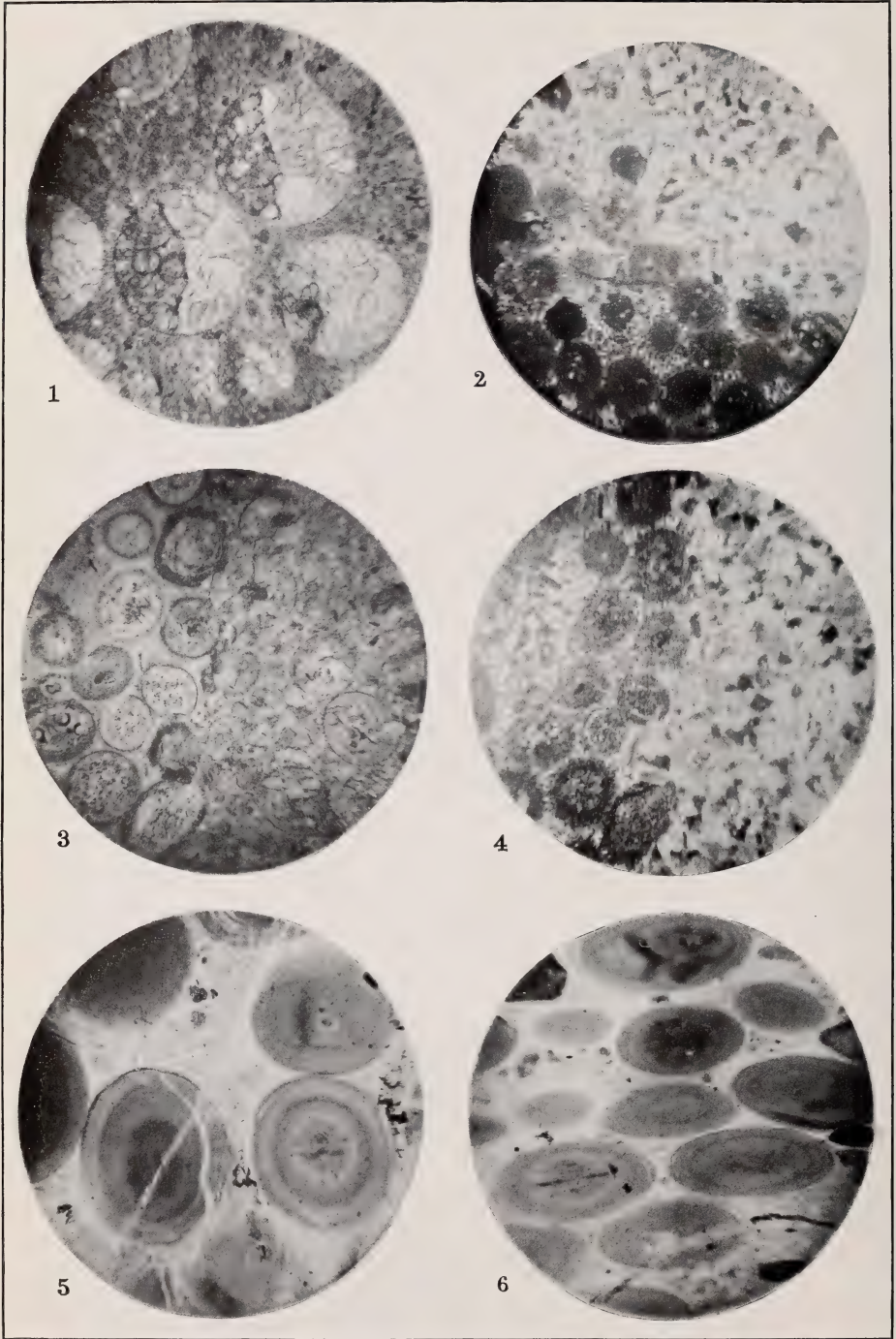


5



6

MICRO-SECTIONS OF OOLITIC STRUCTURE



MICRO-SECTIONS OF OOLITIC STRUCTURE

PLATE 27.—*Micro-sections of oolitic Structures*

FIGURE 1.—Calcareous oolites from the Cambro-Ordovician limestones north of Bethlehem, Pennsylvania.

The recrystallization is complete. About one-half of each oolite is dark, the remainder pure white. No explanation of this can yet be offered. $\times 15$.

FIGURE 2.—Section from the margin of an oolitic chert nodule from the Upper Beekmantown, Bellefonte, Pennsylvania.

Nicols crossed. $\times 15$. This shows numerous rhombic crystals of dolomite in the siliceous oolites and the granular dolomitic ground-mass.

FIGURES 3 AND 4.—Another section similar to that shown in figure 2.

Figure 3, with plain light; figure 4, with crossed nicols. These figures show the zones of rhombohedral crystals around the oolites.

FIGURES 5 AND 6.—Siliceous oolites from the Cambro-Ordovician beds north of Bethlehem.

Figure 6 is from a section of the same specimen as figure 5, but cut perpendicular to that section. This shows the flattening which these oolites have suffered under dynamic action.

The sections illustrated by figures 1, 5, and 6 were loaned to the writer by Mr. F. J. Keeley, Curator of the Vaux Mineral Collection in the Academy of Natural Sciences, Philadelphia.

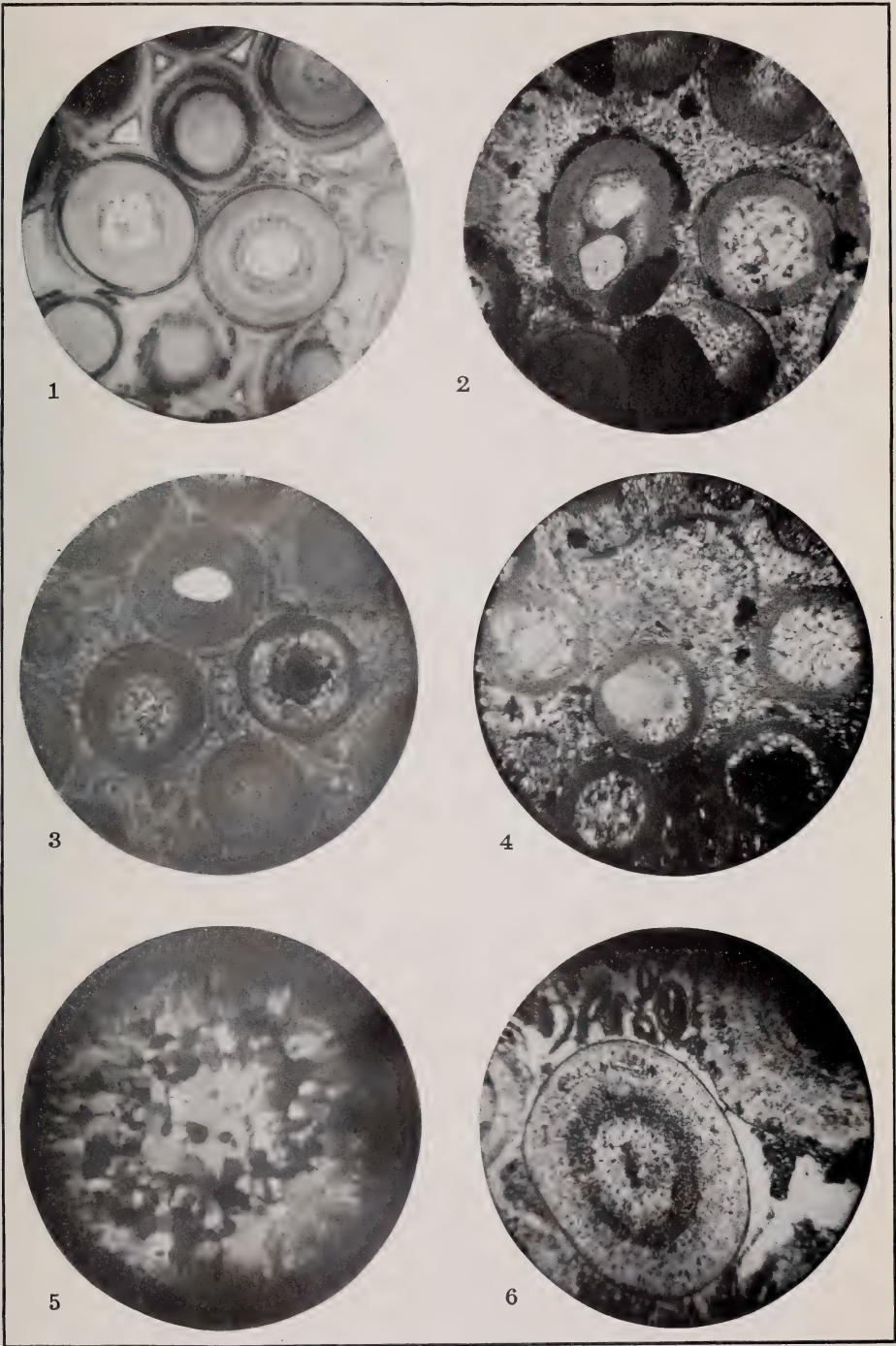
PLATE 28.—*Micro-sections of oolitic Structures*

FIGURES 1 TO 5.—Siliceous oolites from State College, Pennsylvania.

All figures except 5 $\times 20$. Figure 1 is with plain light and shows the bands of iron oxide. In figure 2 one of the oolites has two sand grains in its center; nicols crossed. Figure 3 shows four types of sections from these oolites. In one there is a sand grain secondarily enlarged and showing a quartz crystal outline and a zone of minute rhombic crystals within this enlargement. Another oolite has a plain sand grain at the center, a third a granular center, and a fourth a fibrous center (see text-figure 1). Nicols crossed. Figure 4 shows three oolites with enlarged sand-grain nuclei; nicols crossed. Figure 5 is the center of the granular oolite grain of figure 3. $\times 100$.

FIGURE 6.—Siliceous oolite from Bitter Creek, Wyoming.

Showing foraminiferal skeletons in the interspaces. $\times 20$.



MICRO-SECTIONS OF OOLITIC STRUCTURE

INDEX TO VOLUME 25

	Page		Page
AA lava, Formation of.....	641	AMERICA, Record of storminess in.....	499
—lavas, Chronological table of.....	629	AMERICAN area of storm shifting, Chart of.....	512
ABBOTT, C. G., cited on solar radiation.....	83	—Geological Society, Organization of.....	160
—sun-spots' relation to climatic changes.....	485	—Museum of Natural History, Geological investigation directed by.....	355
—volcanoes' relation to climatic changes.....	483-484	AMI, H. M., Discussion of intraformational corrugation by.....	37
ADAMS, F. D., Acted as toastmaster at annual dinner.....	80	—origin of Saratoga mineral waters by.....	38
—cited on magmatic assimilation.....	261	AN alternative explanation of the origin of the Saratoga mineral waters; R. Ruedemann.....	38
—, Discussion of magmatic differentiation by.....	46	ANALYSIS of Adirondack rocks.....	250
—, Graphic method of representing the chemical relations of a petrographic province.....	43	—clastic material.....	692-730
ADAMS, N. K., Analysis of Adirondack rock by.....	251	—sediments, Methods of.....	657
ADHEMAR, —, cited on gravitational attraction of glacial ice-body.....	223	—concretions; L. J. Youngs.....	79
ADIRONDACK region, Magmatic differentiation and assimilation in....	45, 243	—granites.....	466
—, Petrology of.....	244	—oolitic sand of Great Salt Lake.....	758
ADIRONDACKS, New point in the geology of the.....	47	—Pennsylvania oolite.....	767
AFRICA, Changes of climate in....	528, 541	—oolitic limestone.....	758
—, Inclosed lakes of.....	563	—pyrotherium fauna; F. B. Loomis.....	140
—, Reference to climatic changes in....	482	—quartz rock and felsite.....	473
AFRICAN dinocephalians' relation to American pelycosaur.....	143	—Quincy granite.....	466
AGASSIZ, A., Reference to explorations by.....	166	—riebeckite-agerite granite.....	466
AGE of the Don River glacial deposits, Toronto, Ontario; G. F. Wright.....	205	—Salt Lake water.....	754-755
—glacial deposits in the Don Valley, Toronto, Ontario; G. F. Wright.....	71	—Sokotra granite.....	466
ALABAMA, Geological work in.....	168	ANDERSON, F. M.; Fauna of the Oligocene (?) of Oregon.....	154
—, Reference to Eocene shells from.....	161	—presided at meeting.....	150
ALASKA, Cambrian or pre-Cambrian sedimentary rocks of.....	187	ANDERSON, T., cited on origin of pillow lavas.....	610, 644
—, Carboniferous rock formations of.....	196	ANGLO-PARISIAN basin, Typical character of.....	341
—, Devonian-Cambrian limestones and dolomites of.....	190	ANIMAS formation.....	338
—, Mesozoic-Pennsylvanian, Orange groups of.....	201	ANTELOPES in the fauna of the Rancho La Brea; A. C. Chandler.....	155
—, Permo-Carboniferous (?) conglomerate of.....	199	ANTICOSTI formation, Relation of the Cataract to the.....	291
—, Pillow lavas of.....	619	APPARENT limits of former glaciation in the northern coast ranges of California; R. S. Holway.....	120
—, Pre-Cambrian metamorphic rocks of.....	184	A PRE-CAMBRIAN unconformity in Vermont; A. Keith.....	39
—, Quaternary deposits of.....	202	ARAPAHOE and Laramie, Erosion interval between.....	347
—, Submarine topography in Glacier Bay.....	88	—beds.....	325
ALASKA-YUKON boundary, Geological section along the.....	179	—flora.....	331-333
—, Igneous rocks of.....	203	ARCTIC Ocean, Reference to climatic changes in.....	482
—, Paleozoic section of.....	137	ARCTOWSKI, H., cited on changes in temperature distribution.....	5-48
ALBERTA, Cretaceous-Eocene correlation in.....	355	—cited on climatic changes.....	482
ALBION formation.....	286	—cited on sun-spots' effect on solar heat.....	488-489, 492
ALBERTA, Post-Cretaceous floras of.....	334	—cited on temperature movements.....	83
ALDRICH, F. H., Reference to southern geological work by.....	163	ARCULATE mountains, Mechanics of formation of.....	30
ALGONKIAN, Rocks of the.....	40	ARGENTINA, Glaciation in.....	31
ALLEN, J. H., Geological work in Florida of.....	174	ARIZONA, Erosion and deposition in.....	125
ALLEN, R. C., cited on elliptical greenstone schists.....	612	—, Record of rainfall in.....	535
AMEGHINO, —, cited on dinosaurs.....	401	ARKANSAS, Geological work in.....	166
AMENDMENTS to the by-laws.....	49	ASHLEY, G. H., Geological work in Tennessee of.....	168
		ASHTON schists.....	440, 442
		ASIA, Climatic changes in.....	480
		—, Effects of sun-spots on climate in.....	549
		—, Inclosed lakes of.....	563
		ATWOOD, W. W.; Early Tertiary glaciation in the San Juan region of Colorado.....	31

	Page		Page
AUDITING Committee of Geological Society.....	5	BONNEY, T. G., cited on spheroidal serpentine.....	601
—Paleontological Society.....	133	—structure.....	634
BAILEY, J. W., Geological work in Florida of.....	174	BORKHOLM formation.....	286
BAIN, H. F., Discussion of Great Basin deformations by.....	122	BORNITE, Composition of.....	90
BAKER, C. L., Acknowledgments to.....	77	BOUNDARY between Cretaceous and Tertiary in North America as indicated by stratigraphy and invertebrate faunas; T. W. Stanton.....	341
—; Nature of the later deformations in certain ranges of the Great Basin.....	122	BOUNDEY, E. S., Title of paper by.....	124
BALL, —, cited on contact of Upper and Lower Laramie.....	328	BOWEN, N. L., Crystallization of certain pyroxene-bearing artificial melts.....	91
BARBER, R. A., Analysis of quartz rock and felsite by.....	473	BOWEN, C. F., Reference to dinosaurs found by.....	328-329
—cited on Diamond Hill quartz deposits.....	471	—cited on triceratop-bearing beds.....	348
BARBOUR, E. H., Analysis of Pennsylvania oolites by.....	767	BOYD, D., Reference to.....	163
—cited on oolites.....	760-761	BRACHIOPODA, Cambrian.....	137
BARITE from the Saratoga oil fields.....	77	BRADLEY, —, Geological work in Georgia of.....	174
BARLOW, A. E., cited on Lake Huron volcanic rocks.....	254	BRAHE, Tycho, Reference to meteorologic observations of.....	549-550
—cited on magmatic assimilation.....	261	BRANNER, J. C., elected chairman of Cordilleran Section.....	125
BARNETT, V. R., cited on geology of Indian reservations.....	350	—, Geological work in Arkansas of.....	167
BARROW, G., cited on the vesicularity of lavas.....	651	BRASSFIELD formation, Relation of the Cataract to the.....	291
BARTRAM, W., Coastal Plain work of.....	159	—Sea, Paleogeography of.....	292
—, Geological work in Florida of.....	174	BRAUNS, R., cited on pillow structure.....	598
—Georgia of.....	173	BRAZIL, Reference to glaciation in.....	31
—Louisiana of.....	172	BRIGHAM, A. P., cited on glacial phenomena in Hudson and Mohawk valleys.....	70
—Texas of.....	164	BRITISH AMERICA, Pillow lavas of.....	611
BASCOM, F., Introduction of F. C. Brown by.....	58	—ISLES, Pillow lavas of.....	601
BASIN region, Oligocene of.....	153	BRONTOTHERIUM, New method of restoring.....	140, 406
—, Pacific Coast Tertiary formations, Correlation of.....	156	BROOKS, A. H., cited on agriculture in geological reports.....	161
BASSLER, R. S., Discussion of Alaska Paleozoic section by.....	137	—Nasina series of Alaska.....	186
—new paleogeographic maps by.....	136	—Nation River formation of Alaska.....	199
BAVARIA, Pillow lavas in.....	597	—Upper Devonian shales and cherts of Alaska.....	196
BEADNELL, H. J. L., cited on inclosed lakes of Asia.....	563	—, Geological work in Alaska by.....	180
BEARPAW shale.....	346	BROOKS, C. G. P., cited on climatic changes.....	541
BECK, R., cited on ore deposits.....	770	BROOM, R.; Relations of the American pelycosaurs to the South African dinoccephalians.....	143
BECKER, G. F., Reference to speech at dinner by.....	80	—; Note on the American Triassic genus <i>Placerias lucas</i>	141
BELLY River beds.....	369-371	—; Structure and affinities of the multituberculata.....	140
—compared with Judith River beds.....	369	BROWN, B., cited on dinosaur fauna of Lower Edmonton.....	337
—correlated with the Judith River beds.....	380	—Lance formation.....	327
—Fossils from.....	370-377, 379	—Laramie.....	338
—fauna compared with other faunas.....	387	—relation strips of the Edmonton formation.....	392
BELLINGHAM series, Rocks of.....	448-449	—, Collections from Paskapoo beds by.....	388-389
BENTON sandstone.....	345	—, Cretaceous-Eocene correlation in New Mexico, Wyoming, Montana, Alberta.....	355
BERCKHEIMER, F.; Calcareous algae from the Silurian.....	137	—, Discussion of symposium papers by.....	130
—, Discussion of intraformational corrugation by.....	37	—, Reference to symposium paper of.....	130
BERGT, W., cited on oolites.....	760	—investigations by.....	323
BERRY, E. W., appointed Secretary for Group B. Second Section.....	39	BROWN, T. C., cited on decomposition of marine algae.....	271
—cited on Wilcox flora.....	332, 333	—, Discussion of Adirondack geology by.....	47
BIBLIOGRAPHY of formation names.....	50	—elected to Paleontological Society.....	134
BIGELOW, F. H., cited on storm tracks.....	509	—; Origin of oolites and the oolitic texture of rocks.....	58, 745
BELGIUM, Reference to formations along north coast of.....	321	BRÜCKNER, —, Reference to 35-year cycle of.....	563
—mammal-bearing horizons in.....	323	BRUMBY, —, Reference to assistance rendered Sir Charles Lyell.....	163
BIOTITE granites of Diamond Hill-Cumberland district.....	459	BRYANT, H. C.; Vertebrate fauna of the Triassic limestones at Cow Creek, Shasta County, California.....	155
BLACKVELDER, E., cited on oolitic limestones.....	74		
BLAKE, J. F., cited on pillow lava.....	602		
BLAKE, W. P., Reference to fossil shells collected in California by.....	162		
BOLTON, W. S., cited on pillow lavas.....	605		

	Page		Page
BRYANT, WILLIAM L., elected to Paleontological Society.....	134	CAMBRIAN and Ordovician faunas of southeastern Newfoundland; G. van Ingen.....	138
BUDDINGTON, A. F.; Reconnaissance of the Algonkian rocks of southeast Newfoundland.....	40	— conglomerate.....	268
BEEKLY, A. L., cited on geology of Indian reservations.....	350	— brachiopoda. Comparison of lithologic, stratigraphic, and geographic range of.....	428
— triceratops-bearing beds.....	348	— List of.....	424-427
BUCKLEY, —, Reference to geological work of.....	166	— fossiliferous localities of Diamond Hill-Cumberland district.....	444
BULBOUS budding. Theory of origin of pillow lavas by.....	646	— of western North America; C. D. Walcott.....	130
BURCHARD, —, cited on oolitic iron ores.....	769	— rocks of Diamond Hill-Cumberland district.....	445-446
BURG, L., cited on climatic pulsations.....	532-533	— sedimentary rocks of Alaska.....	187
BURIED gorge of the Hudson River and geologic relations of Hudson syphon of the Catskill aqueduct; W. O. Crosby.....	89	CANADA, Devonian black shale of.....	137
BURLING, L. D.; Cambrian and related Ordovician brachiopoda—a study of their inclosing sediments.....	421	— Edmonton formation of.....	337
— cited on Cambrian fossils from Alaska.....	193	—, Glacial deposits of Don River, Ontario.....	205
—, Discussion of new paleogeographic maps by.....	136	—, Mammal-bearing beds of.....	326
—; Lower Paleozoic section of the Alaska-Yukon boundary.....	137	CAPPS, S. R., cited on ellipsoidal greenstones.....	620
BUTTS, CHARLES, Reference to Warren folio by.....	216	— origin of pillow lavas.....	648
BUWALDA, J. P.; Mammalian fauna of the Pleistocene beds at Manix, in the Mohave Desert region.....	156	CARBONIFEROUS rock formations of Alaska.....	196
BY-LAWS, Amendment to the.....	49	CARNEY, F., Discussion of glacial deposits in Ontario by.....	72
— of the Geological Society.....	97	CARPENTER, W. M., Geological work in Louisiana of.....	172
CABOTS HEAD section, Ontario.....	319	CARRUTHERS, D., cited on inclosed lakes of Mongolia.....	562
— shale.....	280	CASE, E. C.; Evidence of climatic oscillation in the Permo-Carboniferous beds of Texas.....	41
CAIRNES, D. D.; Geological section along the Yukon-Alaska boundary line between Yukon and Alaska rivers.....	179	CATARACT formations of New York and Ontario.....	277
— cited on the Raquet group of Alaska.....	198	— in Ontario, Contacts of the [plate 14].....	287
CAIRNS, F. L., Description and analysis of minerals by.....	467	—, Medina and Clinton, Contact between.....	292
CALCAREOUS algae from the Silurian; F. Berckheimer.....	137	—, Relation to other Siluric faunas of the.....	290
CALIFORNIA, Charts of climatic changes in.....	530	— Sea, Paleogeography of.....	295
—, Contact metamorphic minerals in.....	125	— section, Ontario.....	317
—, Cretaceous-Tertiary, Contact in.....	343	CATESBY, —, Geological work in Florida of.....	174
—, Glaciation on the northern coast ranges of.....	120	CATSKILL aqueduct, Geologic relations of Hudson syphon of the.....	89
—, Gold in granodiorite of.....	124	— Mountains, Divergent ice-flow on the plateau northeast of the.....	68
—, Martinez Eocene of.....	154	CAUSE of the postglacial deformation of the Ontario region; J. W. Spencer.....	65
—, Method of determining age Tertiary formations in.....	152	CEYLON, Reference to climatic changes in.....	482
—, Miocene dolphin from.....	142	CERATOPS beds.....	325
—, Pillow lavas of.....	618	— misnamed.....	356
—, Relation between Cretaceous and Tertiary of.....	152	— fauna, Relationships of.....	337
—, Oligocene and Eocene in.....	153	CENTRAL AMERICA, Climatic changes in.....	539
—, Triassic limestones, Fauna of the.....	155	CEPHALOPODS, Restoration of Paleozoic.....	136
—, Vaqueros of southern.....	153	CERNAYSIEN beds of France and Belgium.....	323
—, Variations in rainfall in.....	121	— fauna.....	395
CALORIC <i>versus</i> cyclonic form of solar hypothesis.....	521	CHADWICK shales.....	285
CALVERT, W. R., cited on erosion surfaces in South Dakota.....	326	CHALMERS, R., cited on non-glaciation of Magdalen Islands.....	84
— geology of Indian reservations.....	350	CHANDLER, A. C.; Antelopes in the fauna of the Rancho La Brea.....	155
—, Lance formation.....	330	CHANGES in climate of Africa and the Americas.....	541
—, Livingston formation of Montana.....	346	— California, Charts of.....	530
— stratigraphic relations of Livingston formation.....	346	—, Effect on glacial period of.....	556
CAMBRIAN and related Ordovician brachiopoda—a study of their inclosing sediments; L. D. Burling.....	421	— precipitation.....	542
		— the crystallographical and optical properties of quartz with rise in temperature; F. E. Wright.....	44
		CHARACTERISTICS of a corrosion conglomerate; F. W. Sardeson.....	39, 265
		CHART of changes in California climate.....	530
		— cloudiness and temperature anomalies.....	582-583

	Page		Page
CHART of comparative storminess during period of maximum and minimum sun-spots.....	545-546	COASTAL subsidence. The problem of...	59
— distribution of loess by De Martonne.....	575	COHN, F., cited on formation of pisolite	747
— European storminess during sun-spot changes.....	516, 518, 520	COLE, G. A. J., cited on origin of pillow lavas.....	638
— historic changes in precipitation.....	542	— pillow structure.....	599, 602
— major and minor sun-spot cycles.....	554	— silica replacement.....	608
— storm belt of the United States.....	570	COLEMAN, A. P., Discussion of age of Lake Ontario by.....	36
CHATARD, T. M.; Analyses of oolitic sand from Great Salt Lake by.....	758	— Colorado glaciation by.....	31-32
CHESTER, H. H., Description and analysis of minerals by.....	467	— deformation of Ontario region by.....	66
CHIMNEY Hill formation, Oklahoma.....	75	— earth movement in Minnesota by.....	35
CHRISTMAN, E., cited on titanotheres.....	406	— pillow lava by.....	33
CLAGGET formation.....	340	— Length and character of the earliest interglacial beds.....	71
CLARK, B. L.; Fauna of the <i>Scutella breveriana</i> zone of the Upper Monterey series.....	151	— cited on Carboniferous conglomerate of Alaska.....	201
— San Pablo series.....	152	— glacial features near Toronto.....	206
CLARKE, F. W., Analyses of Salt Lake water by.....	754-755	COLLIER, A. J., cited on Devonian limestone of Alaska.....	193
— cited on oolites.....	759	COLLINGWOOD section, Ontario.....	318
CLARKE, J. M., cited on Albion formation.....	286	COLORADO, Continuity of marine sedimentation in.....	345
— non-glaciation of Magdalen Islands.....	84	— Early Tertiary glaciation in.....	31
— Discussion of coastal subsidence by.....	62	— epoch, Coal-bearing formations of the.....	345
— Paleozoic faunas by.....	135	— epoch, Crustal oscillations during the.....	344
— Silurian system of Ontario by.....	41	— group, Conglomerate of the.....	346
— Illustrations of intraformational corrugation.....	37	— Mammal-bearing beds of.....	325
— recent exposure of Saratoga springs.....	38	— Mesa Verde formation in.....	345
— Phylogenetic development of the <i>Hexactinellid dityosponges</i> as indicated by the ontogeny of an Upper Devonian species.....	138	COMPARISON of the oysters of the lower and upper horizons of the Miocene of the Muir syncline; W. V. Cruess.....	154
— Reference to speech at dinner by.....	80	COMPOSITION of bornite and its relation to other sulpho-minerals; E. H. Kraus.....	90
CLASTIC sediments, Mechanical composition of.....	655	CONCEPTION Bay, Manganese deposits of.....	73
CLEAVELAND, P., Coastal plain geology by.....	160	CONGLOMERATE, Characteristics of a corrosion of the Galena formation.....	265
CLEMENTS, J. M., cited on ellipsoidal basalts.....	614	— Trenton series.....	265
— Ely greenstones.....	615	CONNECTICUT and Hudson valleys, Submergence of the.....	63
— origin of pillow lavas.....	638	— Mastodon found in.....	143
CLENENIN, —, Geological work in Louisiana of.....	173	— Pillow lavas of.....	622
CLIMATIC changes, Effect on Glacial period.....	556	— Valley, Devonian of the.....	126
— in Yucatan and Guatemala.....	539	— Glacial meanders, oxbows, and kettles in.....	232
— Possible explanations of.....	544	— Marine submergence of.....	219
— Solar hypothesis of.....	47-82	CONRAD, T. A., cited on Medina formation.....	285, 286
— oscillations in Permo-Carboniferous beds of Texas.....	41	— sandstone.....	298
— provinces of the United States west of the Rockies; W. G. Reed.....	124	— Geological work of.....	161
— pulsations.....	532	— in Florida of.....	174
— yardstick, Use of trees as a.....	529	— Georgia of.....	174
— zones, Shifting of.....	540-541	— Louisiana of.....	172
CLINTON, Medina, and Cataract, Contacts between.....	292	—, Medina fauna described by.....	288
— oolitic iron ore.....	768	CONRAD's term Niagara sandstone, Reference to.....	286
CLOSE of the Cretaceous and opening of Eocene time in North America; H. F. Osborn.....	321	CONSTITUTION of the Geological Society.....	93
CLOUDINESS in regions having temperature anomalies, Chart of.....	582	COPE, E. D., cited on Judith River fauna.....	393
COAL-BEARING Eocene of western Washington. I. Pierce County; W. F. Jones.....	121	— Paleocene.....	399
— formations of Utah, Wyoming, and New Mexico.....	345	—, Inadequacy of classification of dinosaurs by.....	378
—, Mode of deposition of.....	58	—, Reference to reconstruction of camarasaurus by.....	143
COAST ranges of California, Glaciation in.....	120	COPPER Mine Hill, Geological section through.....	469
COASTAL Plain geology, Pioneers in.....	157	CORAL-REEF tract of Florida compared with other coral-reef areas.....	41
— subsidence in New England.....	61	CORDILLERAN Section, Proceedings of the meeting of the.....	119
		CORNELIUS, E., Coastal Plain geology by.....	160
		—, Geological work in Georgia of.....	173

	Page		Page
CORRELATION of the Tertiary formations of the Pacific coast and basin regions of western United States; J. C. Merriam.....	156	CUMBERLAND Hill, Geological section through.....	471
— typical late Cretaceous and early Tertiary formation.....	393	— quartzites.....	440-442
CORROSION conglomerate, Characteristics of a.....	39	CUMBERLANDITE of Diamond Hill-Cumberland district.....	450
CORSTORPHINE, G. S., cited on Carboniferous conglomerate of Africa....	201	CUSHING, H. P., cited on Adirondack rocks.....	247, 254, 263
COTTING, J. R., Geological work in Georgia of.....	173	—, Acknowledgments to.....	244, 251
COTTON-CULTURE reports of the Tenth Census.....	176	CYCLONIC <i>versus</i> caloric form of solar hypothesis.....	521
COUPER, —, Geological work in Georgia of.....	174	DAKOTAS, Mammal-bearing beds of.....	325
COVEY Hill beaches.....	237	DALE, N. C., Analyses of Milford granite by.....	459
COX, A. H., cited on pillow lava.....	601	—; Manganese deposits of Conception and Trinity bays, Newfoundland....	73
CRAIG, J. I., cited on climatic changes.....	541	DALL, W. H., cited on Upper Oligocene of Florida.....	175
CREDNER, G. R., cited on origin of pillow lavas.....	637	—, Reference to biographical sketch of T. A. Conrad by.....	162
— pillow structure.....	596-597	— Southern geological work of.....	163
CRETACEOUS and Tertiary, California....	152	DALMER, K., cited on pillow structure....	597
— correlated with the European succession.....	394	DALY, R. A., cited on belt terrane of British Columbia.....	189
— in North America, Boundary between.....	341	— magmatic assimilation.....	261
— periods, Division between.....	398	— origin of pillow lava.....	637-638
—, Assignment of Lance formation to.....	353	— structure.....	636
— climate.....	375	— pillow lava.....	611
— Eocene contact in North America....	342	DANA, J. D., cited on Connecticut Valley terraces.....	221
— correlation in New Mexico, Wyoming, Montana, Alberta; B. Brown in the interior province, End of the.....	347	— oolitic sands.....	747-748
— (late) and early Tertiary formation, Correlations of.....	393	— origin of pillow lavas.....	640, 642
— of Montana, Volcanic activity in the.....	346	— submergence of Connecticut Valley.....	64
— of western Europe.....	341	DANIAN beds.....	336
— sedimentation of the interior province.....	343	— deposits.....	342
— Selma chalk.....	332	— stage, Reference to.....	321
— time in North America, Close of the.....	321	DANIEL. (See Danian.)	
— Tertiary boundary in the Rocky Mountain region; F. H. Knowlton.....	325	DARTON, N. H., cited on New Jersey trap sheet.....	623
— problem, Evidence of the Paleocene-vertebrate fauna on the.....	381	—, Report of Committee on Photographs by.....	49
CRIDER, —, Geological work in Mississippi and Louisiana of.....	171	—; Stratigraphy of red beds of New Mexico.....	81
CRINOID arms, Use in studies of phylogeny of.....	135	DATHE, E., cited on pillow structure....	596
CRITICISM of the Hayfordian conception of isostasy regarded from the standpoint of geology; W. H. Hobbs.....	34	DAUBENY, —, cited on spheroidal structure.....	634
CROSBY, W. O.; Buried gorge of the Hudson River and geologic relations of Hudson syphon of the Catskill aqueduct.....	89	DAVIS, C. A., Discussion of oolites by.....	58
— cited on Blackstone series.....	443	—; Some historical evidence of coastal subsidence in New England.....	61
— melaphyre flows of Nantasket.....	621	DAVIS, W. M., cited on pillow lavas....	623
— origin of pillow lavas.....	638	—; Sublacustrine glacial erosion in Montana.....	86
—; Physiographic relations of serpentine, with special reference to the serpentine stock of Staten Island, New York.....	87	DAWSON beds.....	325
CROSS, WHITMAN, cited on the Laramie.....	338	—, Flora of the.....	332
— magmatic assimilation.....	261	— formation, Correlation of the.....	334
— unconformity in the Denver basin.....	329	DAWSON, G. M., cited on Braeburn limestone.....	198
—, Discussion of glaciation in Colorado by.....	32	— term "Laramie".....	359
— Red beds by.....	81	— Willow Creek series.....	361
CRYSTALLIZATION of certain pyroxene-bearing artificial melts; N. L. Bowen.....	91	DAY, A. L., cited on origin of pillow lavas.....	643, 645
CRUESS, W. V.; Comparison of the oysters of the lower and upper horizons of the Miocene of the Muir syncline.....	154	—; Some observations of the volcano Kilauaea in action.....	80
CUMBERLAND-Diamond Hill district in Rhode Island-Massachusetts....	75, 435	DEEPEST boring in West Virginia; I. C. White.....	48
		DEFORMATION of the Ontario region....	65
		DE LA BECHE, H. T., cited on oolitic texture.....	746-747
		DE LAPARENT, —, cited on the Montens of Belgium.....	394
		DELAWARE terraces; N. H. Winchell....	86
		DELESSE, A., cited on pillow lava.....	634
		DELTA, Glacial.....	226, 241
		DE MARTONNE, Chart of distribution of loess by.....	575
		DENCKMANN, A., cited on pillow structure.....	598
		DENVER beds.....	325
		— flora.....	331-333

	Page		Page
DENVER formation, Correlation of the..	334	DUMBLE, E. T., Reference to geological work of.....	166
DERBY, O. A., cited on glaciation in Brazil	31	DUMONT, —, cited on Mæstrichtien stage	321
DESERT waters, Erosive potential of....	88	DUNDAS section, Ontario.....	315
DESHANES, —, cited on extinct molluscan fauna of Paris basin.....	321	DURST, D. M.; Physiographic features of the Haywards rift.....	123
DESOR, —, cited on Danien stage.....	321	DUTTON, C. E., cited on Pahoehe lava	639, 641
DEVONIAN igneous rocks.....	452-461		
— of Upper Connecticut Valley; C. H. Hitchcock	126	EAGLE sandstone.....	346
— species of <i>Hexactinellid dictyosponges</i> , Development of.....	138	EAKLE, A. S., Discussion of Nevada stibnite by.....	126
DEVONIC black shale of Michigan, Ohio, Canada, and Western New York interpreted as a paleozoic delta deposit; A. W. Grabau.....	137	— — — nomenclature by.....	125
DEVONO-CAMBRIAN limestones and dolomites of Alaska.....	190	—, presided at meeting.....	123
— ORDOVICIAN shale of Alaska.....	195	—; Some contact metamorphic minerals in crystalline limestone at Crestmore, near Riverside, California....	125
DEWEY, H., cited on origin of pillow lava and structure.....	636, 638	EARLY Tertiary glaciation in the San Juan region of Colorado; W. W. Atwood	31
— pillow lava.....	604, 606-607	EARTH movements in the Minnesota portion of the Lake Agassiz basin during and since the lake occupancy; F. Leverett.....	34
D'HALLORY, —, Introduction of term Cretaceous by.....	336	EARTHQUAKES in Panama and their causes	34
DIABAS dikes in Diamond Hill district..	474	EARTHQUAKE sea waves; H. F. Reid....	33
DIAMOND Hill-Cumberland district, Glaciation in.....	438	EAST INDIES, Pillow lavas of.....	610
— — — in Rhode Island-Massachusetts	435	EASTMAN, C. R., elected representative on Supervisory Board of American Year Book.....	134
— — —, Petrography of.....	449	EATON, AMOS, cited on Medina formation	287, 297
— — —, Table of rock formations of.....	439	ECKEL, —, Geological work of.....	171
— — — felsite	461	ECHINODERMS of the San Pablo; W. S. W. Kew.....	152
— — — quartz deposits.....	471	EDMONTON formation.....	362-368
DIASTROPHISM and migrations of fauna. DICKERSON, R. E., cited on Cretaceous-Eocene boundary.....	397	—, Description and fossils of the.....	373-376
—; Faunal relations of the San Lorenzo Oligocene to the Eocene in California	343	—, Fossils of.....	365-367
— — — zones of the Martinez Eocene of California	153	— — — intermediate between Judith River and Lance.....	380
DIGHTON group of Narragansett series.....	447	— formations of Canada.....	337
DILLER, J. S., cited on oolites.....	761	EDMONTON-PIERRE contact.....	368
DILLON, —, cited on oolites.....	764	—, Fossils from.....	368
DINOSAUR-bearing beds.....	325	— — —, Geologic section of.....	369
— faunas' relationship to the unconformity separating Cretaceous and Tertiary	337	— section, Fossil plants of the.....	337
DINOSAURS as evidence of Cretaceous age	337	EDWARDS, W. S., Acknowledgments to.....	48
— in Tertiary formations.....	400	EFFUSIVE and intrusive in the quantitative classification; A. C. Lane.....	43
—, Occurrence and absence of.....	337	ELECTION of Officers and Fellows.....	5, 6
—, Reference to absence and occurrence of	334	ELEPHANTS, Restoration of.....	142
—, Undetermined classification of formations containing.....	342	— — — the world series of.....	407-410
D'INVILLIERS, E. V., cited on Pennsylvania oolites.....	760	ELDRIDGE, G. H., cited on structural breaks in Denver basin.....	345
DIVERGENT ice-flow on the plateau northeast of the Catskill Mountains as revealed by ice-molded topography; J. L. Rich.....	68	ELLS, R. W., cited on pillow lava.....	611
DOLLO, —, cited on the Danien and Montien	336	EMERSON, B. K., cited on basalt sheet of Deerfield.....	622
— — — Montian	396	— — — Bellingham series.....	449
— — — of Belgium.....	394	— — — granite dike.....	468
DOLOMITE, Origin of.....	66	— — — Milford granite.....	454
DON River beds, Character of fossils found in.....	210	— — — porphyry	463
— — — Glacial deposits.....	200	— — — pillow lava.....	628-629
D'ORBIGNY, —, cited on demarcation between Cretaceous and Eocene....	321	— — — Pleistocene features of Connecticut Valley.....	220, 224
DOUGLASS, A. E., cited on relation of precipitation to tree growth.....	529	— — — submergence of the Connecticut Valley.....	63
— — — tree measurements.....	495	—, Mapping of quartz diorite area by.....	452
— — —, Reference to 21-year cycle of.....	563	—, Work in the Diamond Hill-Cumberland district by.....	441
DOUGLASS, E., cited on Fort Union fauna	389	EMMONS, E., Geological work of.....	160
—; Geology of the Uinta formation, 144, 417	762	—, State geologist of North Carolina..	160
DREWE, —, cited on origin of oolites....	762	EMORY, W. H., Reference to Mexican boundary survey by.....	165
DUMBLE, E. T., Acknowledgments to...	77	ENGLAND, Pillow lavas in.....	603
		ENGLISH, W. A., Fauna of lower Fernando series.....	151
		Eocene and Oligocene of California, Relations of.....	153
		— climate	375

	Page		Page
Eocene-Cretaceous contact in North America.....	342	FAUNA of the <i>Scutella breweriana</i> Zone of the Upper Monterey series.....	151
— correlation in New Mexico, Wyoming, Montana, Alberta.....	355	FEATHERSTONHAUGH, G. W., Geological researches of.....	163
— faunas, Progress in revision of.....	144	FELLOWS, Election of.....	6
— (middle and upper) fauna compared with other faunas.....	387	FENNEMAN, N. M., Discussion of intraformational corrugation.....	37
— Lemuroid, Skeleton of.....	141	—, Preglacial Miami and Kentucky rivers.....	85
— of California, Martinez.....	154	FENNER, C. N., cited on pillow lava.....	624, 628
— the Gulf region, Correlation of the marine.....	334	—; Mode of formation of certain gneisses in the highlands of New Jersey.....	44
— Washington, Coal-bearing.....	332	—, N. L. Bowen introduced by.....	91
— western Europe.....	341	FERNANDO series, Fauna of Lower.....	151
— midway formations.....	332	FINAL results in the phylogeny of the titanotheres; H. F. Osborn.....	139
— shells from Alabama, Reference to.....	161	FLATTENING of limestone gravel boulders by solution; J. A. Udden.....	66
— time in North America, Opening of.....	321	FLETT, J. S., cited on origin of pillow lavas and structure.....	636, 644
EOTITANOPS, New method of restoring.....	140, 406	— — pillow lava.....	604, 606-607
EROSIVE potential of desert waters; Charles Keyes.....	88	FLORIDA coral-reef tract compared with other coral-reef areas.....	41
ETAGE 5 formation of Norway.....	286	—, Geological work in.....	174
ETTINGER, A. E., Photographs of glacial topography by [plate 9].....	215	FOERSTE, A. F., Cambrian boulders found by.....	460
EUROPEAN Cretaceous and Eocene.....	341	— cited on fauna of Brassfield formation.....	291
— storminess during sun-spot changes, Chart of.....	518	— — fossiliferous localities of Diamond Hill-Cumberland district.....	444-446
— — maximum and minimum.....	520	—, Discussion of phylogeny of crinoids by.....	135
— Chart of.....	335	—, Work in the Diamond Hill-Cumberland district by.....	438
— time scale.....	500	FONTAINE, W. M., Bibliography of.....	10
EUROPE, Chart of storm tracks in.....	500	—, Memorial of.....	6
— storminess during sun-spot changes.....	516	—, Photograph of.....	6
—, Effect of sun-spots on climate in.....	549	FORMATION names, Bibliography of.....	50
—, Record of storminess in.....	499	FORSHEY, C. G., Geological work in Louisiana of.....	172
EVENIS leading up to the organization of the Geological Society of America; J. J. Stevenson.....	15	FORT Union fauna, Characters of the.....	389-390
EVIDENCE of a glacial dam in the Allegheny River between Warren, Pennsylvania, and Tionesta; G. F. Wright.....	84, 215	— — flora.....	334
— climatic oscillations in the Permian-Carboniferous beds of Texas; E. C. Case.....	41	— — formation, Correlation of the.....	334
— the Paleocene vertebrate fauna on the Cretaceous-Tertiary problem; W. D. Matthew.....	381	FOSSIL deposits of Macclesfield, England.....	211
EYMAR, —, cited on demarcation between Cretaceous and Eocene.....	321	— — Moel Tryfaen, Wales.....	210-211
FAIRCHILD, H. L., Discussion of glacial deposits in Ontario by.....	72	— — fucoids.....	272
—; Pleistocene marine submergence of the Connecticut and Hudson valleys.....	63, 219	— — graptolites from Alaska.....	194
—; Review of the early history of the Society.....	17	— — localities of Diamond Hill-Cumberland district.....	444
FAROE ISLANDS, Pillow lavas of.....	610	— — sponges.....	272
FARRINGTON, O. C., Discussion of change in quartz through rise of temperature by.....	44	FOSSILS from Belly River beds.....	370
— — oolites of Chimney Hill formation by.....	76	— — Edmonton-Pierre contact.....	368
— — Park City minerals by.....	48	— — Red Deer River district, Canada.....	362
FASSIG, —, cited on tropical hurricanes.....	494	— — the Lance formation.....	352
FAUNAL migrations and diastrophism.....	397-399	— — Paskapoo beds in Alberta.....	389
— relations of the San Lorenzo Oligocene to the Eocene in California.....	153	— — Upper Fort Union beds.....	389-390
— zones of the Martinez Eocene of California; R. E. Dickerson.....	154	— of Cataract fauna.....	281-285
FAUNA of lower Fernando series; W. A. English.....	151	— — Cernaysian fauna.....	395
— the Cumberland Pleistocene cave deposit; J. W. Gidley.....	142	— — Don River beds.....	210
— — Oligocene (?) of Oregon; F. M. Anderson.....	154	— — Edmonton formation.....	365-367, 374-376
— — San Pablo series.....	152	— — Galena formation.....	270
		— — Hell Creek formation.....	357-359
		— — Medina fauna.....	288-290
		— — Ojo-Alamo beds.....	379-380
		— — Paleocene formations of Europe.....	322
		— — Paskapoo formation.....	371-373
		— — titanotheres.....	403-405
		— — on Long Island, Reference to.....	242
		— — Paleocene vertebrate.....	383-385
		FOSTER, R. C., cited on riebeckite granite.....	470
		FOWLE, F. E., cited on solar radiation.....	83
		— — volcanic relation to climatic changes.....	483-484
		FOX, H., cited on pillow lava.....	603, 605
		FOX Hills formation, Relationship of the Pierre to the.....	356

	Page		Page
FOX Hills sandstone.....	350	GLACIAL drift on Magdalen Islands....	84
— section	330	— erosion in Montana.....	86
FRANCE, Reference to mammal-bearing horizons in.....	323	— ice-dam in Allegheny River.....	84
—, Pillow lavas of.....	599	— Lake Missoula; R. W. Stone.....	87
FREE, E. E., cited on climatic changes in Southwest.....	558-562	— meanders, ox-bows, and kettles in the Connecticut Valley.....	232
FRITZ, H., cited on sun-spots and related phenomena.....	553	— period, Various hypotheses as to causes of the.....	565-577
FRONTIER formation, Coal-bearing members of the.....	346	—, Connection between changes of climate and.....	556
		— temperatures, Reference to.....	537
		— topography, Glade Run terrace, Pennsylvania [plate 9].....	215
GABBERO of Diamond Hill-Cumberland district	449	GLACIATION and land distribution, Chart of	586
GALE, H. S., cited on climatic changes in Southwest.....	559	— in Argentina.....	31
— — Lake strands.....	564	— — Brazil.....	31
GALENA formation, Conglomerate in the.....	269	— — Colorado, Early Tertiary.....	31
— Trenton series, Conglomerates of the.....	265	— — the northern coast ranges of California.....	120
GARDINER, C. I., cited on pillow lavas.....	608	— of the Permian period.....	578-588
GARDNER, —, cited on Puerco and Torrejon fauna.....	401	GLACIER Bay, Submarine topography in.....	88
GARNETIFEROUS hornblende schist of New Hampshire.....	75	GLAUCONITE, Genesis of.....	91
GEIKIE, A., cited on Cretaceous of England	341	GLENN, L. C., Geological work in Tennessee of.....	168
— — lithologic sequence in France and England.....	336	GLENWILLIAM section, Ontario.....	317
— — origin of pillow lavas.....	638-650	GNEISSES of New Jersey, Mode of formation of.....	44
— — pillow lava.....	602, 603, 605, 606, 607, 608, 609, 610-635	GOODE, G. B., Reference to writings of.....	159
— — structure of lavas.....	592-593	GOODSPEED, JR., G. E., cited on pre-Cambrian gabbro.....	450
— — Rhone glacier.....	491	GOLDTHWAIT, J. W., Discussion of coastal subsidence by.....	62
GEIKIE, JAMES, cited on spheroidal structure	610	— — submergence of Connecticut and Hudson valleys.....	64
GENESIS of glauconite; C. Palmer.....	91	—, J. W. Merritt introduced by.....	75
GEOLOGIC history of the coral-reef tract and comparisons with other coral-reef areas; T. W. Vaughan.....	41	—, Occurrence of glacial drift on the Magdalen Islands.....	84
GEOLOGICAL relations between the Cretaceous and Tertiary of southern California; C. A. Waring.....	152	GORDON, C. H., Geological work in Tennessee of.....	168
— section along the Yukon-Alaska boundary line between Yukon and Porcupine rivers; D. D. Cairnes.....	179	GRABAU, A. W., cited on Niagara Gorge section.....	308
GEOLOGY of the Diamond Hill-Cumberland district in Rhode Island-Massachusetts; C. H. Warren and S. Powers	75, 435	— cited on Medina fauna.....	281, 285, 286
— — southern end of the San Joaquin Valley; G. C. Gester.....	123	— — formation.....	302
— — Uinta formation; G. Douglass.....	144-417	— — origin of pillow lavas.....	639
— — Wabana iron ore of Newfoundland; A. O. Hayes.....	74	— — pillow structure.....	635
GEORGIA, Geological work in.....	173	— — Queenston.....	287
GERMANY, Pillow lavas in.....	595	—, Devonian black shale of Michigan, Ohio, Canada, and western New York interpreted as a Paleozoic delta deposit.....	137
GESTER, G. C., Geology of the southern end of the San Joaquin Valley.....	123	—, Discussion of Silurian system of Ontario by.....	41
GIDLEY, J. W., cited on Fort Union fauna	389	— — philogeny of crinoids by.....	135
—, Discussion of Multituberculata by.....	140	— — Permo-Carboniferous beds of Texas.....	41
—, Fauna of the Cumberland Pleistocene cave deposit.....	142	— — coastal subsidence by.....	61
GILBERT, G. K., cited on land subsidence	60	—, Fossils of the Cataract formation described by.....	289
— — washing of sediments.....	730, 755-756	—, Some new paleographic maps of North America.....	136
—, Reference to Niagara Falls pictures by.....	36	— suggests replacement of "Grey Band" by Thorold sandstone.....	297
GILBERT Gulf beaches.....	237	GRAFTON quartzite.....	441
GILMER, F. W., Coastal Plain geology by.....	160	GRANITES, Analyses of.....	466
GLACIAL dam in the Allegheny River, Pennsylvania	215	GRANT, C. C., Acknowledgments to.....	278
— deltas	241	GRANT, U. S., cited on ellipsoidal greenstones	619
—, terraces, and detritus of the Connecticut Valley.....	226-229	—, Member of Auditing Committee.....	49
— deposits in the Don Valley.....	71	GRANTS Mill granite of Diamond Hill-Cumberland district.....	458
— of Don River.....	205	GRANGER, WALTER, cited on Ojo Alamo beds	379
		— — Paleocene vertebrate fauna.....	382
		— — Torrejon fauna.....	401
		—, Reference to Eocene collections by.....	144
		GRAPHIC method of representing the chemical relations of a petrographic province	43
		GRAVEL boulders of limestone, Flattening of.....	66

	Page		Page
GREEN, W. L., cited on Hawaiian lava flows of 1859.....	33	HARKEN, A., cited on origin of pillow lavas.....	639
— origin of pillow lavas. 640-641.....	644	— pillow structure.....	635
GREENLY, E., cited on pillow lava.....	602	HARTNAGEL, C. A., cited on Medina formation.....	302
GRIMSBY section, Ontario.....	310	— oolitic iron ore.....	768
GREAT basin, Later deformations in certain ranges of the.....	122	HATCH, F. H., cited on Carboniferous conglomerate of Africa.....	201
GREAT BRITAIN, Reference to glacial geology of.....	214	HATCHER, J. B., Reference to fossils collected by.....	393
GREAT Lake history.....	35	HAWES, G. W., Geological work in Florida of.....	175
GREGORY, H. E., cited on sand plains of Naugatuck Valley.....	238	HAWVER, J. C., Some physical features of Hawver cave.....	153
— spheroidal lavas in Maine.....	621	HAY, —, cited on Fort Union fauna.....	389
— veins of chalcopryrite and galena.....	474	— position of Puerco and Torreyson formations.....	399
GREGORY, J. W., Chart of historic changes in precipitation prepared by.....	542-543	HAYES, A. O.; Geology of the Wabana iron ore of Newfoundland.....	74
— cited on changes in precipitation. 536-537.....	536-537	HAYFORDIAN conception of isostasy, Criticism of.....	34
— climatic changes in Asia.....	480	HAYNES, W. P., cited on age of Narragansett series.....	448
— pulsations.....	532-533	— pre-Cambrian gabbro.....	450
— origin of pillow lavas.....	638	HAYWARDS Rift, Physiographic features of the.....	123
— pillow structure.....	597, 599	HEADDEN, W. P., cited on Doughty Springs of Colorado.....	79
— titanotheres.....	144, 406	HEDEN, SVEN, cited on climatic pulsations.....	532
— Discussion of Pelycosaurus by.....	143	HELL Creek beds.....	325
—; Phyletic relationships of the lemuroidae.....	141	— similar to the Lance.....	358
—, Reference to materials assembled by.....	411	— synchronous with the Lance.....	380
—, Skeleton of Notharctus, an Eocene lemuroid.....	141	— formation, Fossils of the.... 357-359	357-359
GROUP of twenty-six associated skeletons of leptomeryx from the White River Oligocene; E. S. Riggs.....	145	—, Montana.....	356
GUATEMALA, Climatic changes in.....	539	HEILPRIN, A., Geological work of.....	161
GUELTIARD'S mineralogical map of Louisiana and Canada.....	161	HEINECK, F., cited on pillow structure.....	598
"GUMBO," Mechanical analysis of.....	729	HENDERSON, —, cited on climatic changes.....	548
GWILLIM, J. C., cited on Cache Creek group of British Columbia.....	198	HENLEY, A. S., Discussion of coast range glaciation by.....	121
HALL, B., Reference to Niagara Falls pictures by.....	36	HENRY, A. J., cited on precipitation in the United States.....	538
HALL, C. W.; Analyses of rocks of the Galena-Trenton series.....	270	HERBETTE, F., cited on climatic pulsations.....	532-533
HALL, JAMES, cited on Cataract fauna.....	281	HESSE, Pillow lavas in.....	597
— Clinton formation.....	278	HEWETT, —, cited on climatic changes.....	548
— Medina formation.... 285, 286,	287	HIGGINS, D. F., cited on ellipsoidal greenstones.....	619
— sandstone.....	299	HIGH-LEVEL Loop channel; T. C. Hopkins.....	68
— section.....	306	HILGARD, E. W., Reference to reports by.....	167
— Niagara formation.....	287	—, Southern geological work of.....	170
— Rochester Siluric section.....	304	—, Work on cotton reports of.....	176
—, Geological work in Texas of.....	163	HILL, J. B., cited on pillow lava.....	604
—, Medina fauna described by.....	288	HILL, R. T., Comment on early geological work in Texas by.....	165
—, Reference to survey of the American Falls by.....	36	—, Geological work in Arkansas-Texas region by.....	165
HAMILTON section, Ontario.....	313	HILLEBRAND, W. F., Analysis of Adirondack rocks by.....	251
HAMMOND, H., Work on cotton reports of.....	176	HISTORY of the Bulletin by J. Stanley-Brown.....	24
HAUG, —, cited on Danien stage.....	321	HITCHCOCK, C. H., cited on Connecticut Valley terraces.....	220
— the Danien and the Montien.....	336	— origin of pillow lavas..... 641-642	641-642
HANNIBAL, H., Discussion of Oregon Oligocene by.....	154	—; Devonian of the Upper Connecticut Valley.....	126
—; Yaqueros of the Santa Monica Mountains of southern California.....	153	HITCHCOCK, EDWARD, cited on Connecticut Valley terraces.....	220
HANN, J., cited on climatic changes.....	480, 527	HOBBS, W. H.; Criticism of the Hayfordian conception of isostasy regarded from the standpoint of geology.....	34
— sun-spots' relation to climatic changes.....	492, 494	—, Discussion of coastal subsidence by.....	59, 61
HANOVER, Garnetiferous hornblende schist of.....	75	— earthquake sea waves by.....	33
—, Pillow lavas in.....	597	— pillow lava by.....	33
HARDY, T. S., Engineering work of.....	171	—; Mechanics of formation of arcuate mountains.....	30
HARES, C. J., cited on cannon-ball formation.....	339		
— geology of Indian reservations.....	350, 351		
HARRIS, G. D., Geological work in Arkansas of.....	167		
— Louisiana of.....	173		
—, Reference to southern geological work by.....	163		

	Page		Page
HOFFMANN, F., cited on pillow structure	597	INTRAFORMATIONAL corrugation, Illustrations of	37
HOLLICK, A., Acknowledgments to	356	IRELAND, Pillow lavas in	608
— cited on fossils from Belly River formation	370	IRVINE, —, cited on oolites	759
— fossils of Edmonton formation	366-367	ISSIL, A., cited on pillow structure	599
— fossils of the Edmonton formation	375	ISOSTASY, Criticism of the Hayfordian conception of	34
HOLMES, J. A., State geologist of North Carolina	160	ITALY, Pillow lavas of	599
HOLST, N. O., cited on duration of Glacial period in Sweden	213	JAVA, Reference to climatic changes in	482
HOLWAY, R. S., Apparent limits of former glaciation in the northern coast ranges of California	120	JACKSON, —, Geological work in Georgia of	174
—, Discussion of climatic provinces by	124	JACKSON, C. T., cited on limestone of Diamond Hill-Cumberland district	443
—, Inquiries by	125	— — serpentine	451
HOOPER, R., cited on oolitic texture	745	—, Work in Diamond Hill-Cumberland district by	438
HOPKINS, F. V., Geological work in Louisiana of	172	—, Discussion of phlogeny of crinoids by	135
HOPKINS, T. C., cited on Indiana oolitic limestones	748	—, Meeting presided over by	136
—, High-level loop channel	68	JACKSON, T. M., Memorial of	13
HORNBLÉNDE schist of New Hampshire	75	—, Photograph of	13
HORNE, J., cited on pillow lava	606	JEFFERSON, THOMAS, Reference to Coastal Plain work by	159
HOVEY, E. O., acted as Secretary of First Section	65, 84	JEFFREY, E. C., Improvements in methods of investigating highly carbonized materials and their bearing on the deposition of coal	58
—, C. A. Reeds introduced by	75	JOES Rock granite porphyry and felsite of Diamond Hill-Cumberland district	456
—, cited on oolites	761-762	JOHNSON, B. L., cited on Labradorite porphyry dikes	452
—, Discussion of Staten Island serpentine by	88	— — ellipsoidal greenstones	620
HOWE, E., JR., cited on glacial terraces	223	JOHNSON, D. W., Discussion of intraformational corrugation	37
HUDSON and Connecticut valleys, Submergence of the	63	— — Red Beds by	82
— Bay, Pillow lavas of	612	— — coastal subsidence by	62
— Champlain Valley, Reference to glacial phenomena in	233	— — earthquake sea waves by	34
— River, Buried gorge of the	89	—; Precise leveling and the problem of coastal subsidence	59
— Valley, Marine submergence of	219	JOHNSON, J. H., Work in Diamond Hill-Cumberland district by	438
HUGHES, T. MCK., cited on Moel Tryfan fossils	211	JOHNSON-LAVIS, H. J., cited on origin of pillow lavas	53, 639
HUME, W. F., cited on climatic changes	541	— — pillow lavas	610, 634
HUMPHREYS, W. L., cited on solar radiation	83	JONES, J. C., cited on climatic changes in southwest	558
— — volcanic relation to climatic changes	483-484	—, Discussion of Arizona erosion and deposition by	125
HUNTINGTON, —, cited on Otero Basin terraces of New Mexico	562	—, Inquiries by	125
HUNTINGTON, E., Discussion of coastal subsidence by	60	—; Occurrence of stilbite and metastilbite at Steamboat Springs, Nevada	126
—; Solar hypothesis of climatic changes	82, 477	JONES, O. T., cited on pillow lava	601, 603
ICELAND, Pillow lavas of	608-610	JONES, W. F., Coal-bearing Eocene of western Washington, I. Pierce County	121
IDAHO, Pillow lavas of	617	JUDITH River beds compared with Belly River beds	369
IDINGS, J. P., cited on magmatic assimilation	261	— correlated with Belly River and Ojo Alamo beds	380
— — pillow structure	635	— — fauna, Relations of the	393
—, Discussion of New Jersey gneisses by	45	— — formation	346
— — pillow lava by	33	JUKES, —, cited on spheroidal structure	634
IGNEOUS rocks, Diamond Hill-Cumberland district	449-475	KEELE, J., cited on Cambrian fossils from Alaska	193
— — of Yukon-Alaska boundary	203	— — Macmillan River beds of Alaska	202
ILLUSTRATIONS of intraformational corrugation; J. M. Clarke	37	KEIDEL, —, Discovery of glaciation in Argentina by	31
— — the recent exposure of the Saratoga Springs; J. M. Clarke	38	KRISLEY beds of Britain	286
IMPROVEMENTS in methods of investigating highly carbonized materials and their bearing on the mode of deposition of coal; E. C. Jeffrey	58	KEITH, A.; A pre-Cambrian unconformity in Vermont	39
INDIA, Climatic changes in	481	—, Discussion of Newfoundland Algonkian rocks by	40
INDIAN Meteorological Department cited on climatic changes	481	—, Report of Committee on Geological Nomenclature by	49
INTERGLACIAL beds, The earliest	71		
— epoch in British Isles and in United States	213		
INTERIOR province, Cretaceous sedimentation of the	343		

	Page		Page
KELLERMAN, C. F., cited on bacterial flora of Great Salt Lake.....	59	KULLMER, C. J., cited on cyclones.....	83
KEMP, J. F., Acknowledgments to.....	244	—; Charts of storminess during sun-spot maximum.....	504-509
— cited on Adirondack rocks.....	248, 251, 254, 263	—; Chart of European storminess during sun-spot changes.....	516
— — — origin of spheroidal forms.....	635	—, Compilation of storms by.....	496-497
—, Discussion of bornite by.....	91	—, Law of shift of storm track by.....	502-503
— — — magmatic differentiation by.....	46	KÜMMEL, H. B., cited on New Jersey trap sheet.....	623
— — — method of representing chemical relation of a petrographic province by.....	43	— — — origin of pillow lavas.....	639
— — — New Jersey gneisses by.....	45	KUNZ, G. F., cited on Jasper agate.....	472
— — — Park City minerals by.....	48		
—, F. M. Van Tuyl introduced by.....	66	LABRADORITE porphyry dikes of Diamond Hill-Cumberland district.....	452
—, Meeting of Group C, third section, called to order by.....	43, 73, 90	LABRADOR glacier older than Keewatin.....	212
—, New point in geology of the Adirondacks.....	47	LA FORGE, L., cited on rocks of Bellingham series.....	448
—, Reference to speech at dinner by.....	80	LAHEE, F. H., cited on metamorphism in Diamond Hill-Cumberland district.....	445
KENDALL, P. F., Reference to Moel Tryfaen fossils collected by.....	211	— — — riebeckite granite.....	470
KENNEDY, WILLIAM, Reference to work in Texas of.....	164	— — — rocks of Rattlesnake Hill.....	476
KENTUCKY and Miami rivers, Preglacial.....	85	LAKE AGASSIZ basin, Earth-movements in.....	34
KERR, W. C., State Geologist of North Carolina.....	160	—, Reference to shore line of.....	209
—, Work on cotton reports of.....	176	—, Erie glacial phenomena.....	207, 208
KETTLES in the Connecticut Valley, Glacial.....	232	—, Iroquois, Age of.....	207
KEW, W. S. W., Echinoderms of the San Pablo.....	152	—, Michigan glacial phenomena.....	207, 208
KEWATIN Glacier younger than Labrador Glacier.....	212	—, Missoula, Glacial.....	87
— ice-sheet.....	212	—, Superior region, Pillow lavas of.....	612
KEYES, CHARLES, Erosive potential of desert waters.....	88	—, Warren, Reference to.....	207, 208
KINDLE, E. M., cited on Cambrian fossils from Alaska.....	193	LAMBE, L. M., cited on trachodont skull from Belly River beds.....	380
— — — Devonian limestone of Alaska.....	192	LAMPLEIGH, —, cited on inter-Glacial epoch.....	213
— — — Medina formation.....	287	LANCE and Hell Creek beds, Synchronous.....	380
— — — Nation River formation of Alaska.....	199	— — — Laramie, Unconformity between.....	401
— — — upper Devonian shales and cherts of Alaska.....	196	— — — Creek beds.....	325
—, Geological work on Porcupine River by.....	180	— — — fauna compared with other faunas.....	387
KILAUEA in action, Observations on.....	80	— — — formation.....	323, 325
KING, CLARENCE, cited on the Laramie.....	338	— — — assigned to the Cretaceous.....	353
— — — Uinta group.....	417	— — — Continuity of.....	330
KNIGHT, CHARLES, Reference to restorations by.....	142	— — — Correlation of the.....	334
KNIGHT, C. R., Reference to sculptural work of.....	407	— — — Difficulty of correlating the.....	396
KNOWLTON, F. H., Acknowledgments to.....	356	— — — Distribution, character, and development of.....	348-353
— cited on absence of dinosaurs in the Laramie.....	400	— — — Flora of the.....	331-334
— — — flora of the Puerco formation.....	382	— — — Fossils from the.....	352
— — — Fort Union flora.....	349	— — — Marine member of.....	350
— — — fossils from Edmonton formation.....	366-367, 375	LANE, A. C., Effusive and intrusive in the quantitative classification.....	43
— — — Lance flora.....	396	LANGDON, D. W., Geological work of.....	171
— — — unconformity between Laramie and Lance.....	401	— — — in Florida by.....	174
—; Cretaceous-Tertiary boundary in the Rocky Mountain region.....	325	LARAMIE and Lance, unconformity between.....	401
—, Discussion of symposium papers by.....	130	— formation, Flora of the.....	331-333
—, Identification of fossils from Ojo Alamo beds by.....	379	"LARAMIE?" Puerco and Torrejon in the San Juan basin, New Mexico; W. J. Sinclair.....	138
—, quoted on flora from Lance formation.....	350, 351	— — — unconformity in the Denver basin.....	347
—, Reference to investigations by.....	322	LAWS governing sedimentation.....	732-737
—, Sketch of Fontaine's paleobotanical work by.....	8	LAWSON, A. C., cited on magmatic assimilation.....	261
KÖPPEN, W., cited on sun-spots' relation to solar heat.....	487-488	— — — origin of pillow lavas.....	653
KOST, J., Geological work in Florida of.....	175	— — — pillow lavas.....	611
KROPATKIN, P., cited on climatic changes in Asia.....	480	— — — spheroidal basalts and diabases.....	619
KRAUS, E. H., Composition of bornite and its relation to other sulfominerals.....	90	—, Discussion of Coast Range glaciation by.....	121
		— — — Great Basin deformations by.....	122
		— — — Washington coal-bearing Eocene by.....	122
		—, made temporary chairman of Cordilleran Section meeting.....	120
		LEA, ISAAC, Geological work of.....	160, 161
		LE CONTE Geological Club, Reference to.....	123
		LE CONTE, J., Geological work in Florida of.....	174
		LEE, W. T., Acknowledgments to.....	335

	Page		Page
LEE, W. T., cited on extension of older Cretaceous beds in New Mexico.....	401	LOUDERBACK, G. D., Discussion of nomenclature by.....	125
— the Cretaceous section.....	329	— elected secretary of Cordilleran Section.....	125
—, Discussion of symposium papers by.....	130	LOUGHLIN, G. F., cited on quartz deposits.....	473
LEIDY, —, Inadequacy of classification of dinosaurs by.....	378	— Sterling granite.....	470
LEITER, H., cited on climate of North Africa.....	528	LOUGHBRIDGE, R. H., Work on cotton reports of.....	176
LEITH, C. K., cited on belt terrane of British Columbia.....	189	LOUIS, H., cited on oolitic iron ores.....	770
— origin of pillow lavas.....	638	LOUISIANA, Geological work in.....	170
— pillow lavas.....	612	LOWER Edmonton, Dinosaur fauna of.....	337
— Wisconsin volcanic rocks.....	253	— Fort Union beds.....	325
LEMUROIDEA, Phyletic relationships of the.....	141	— Miocene of Washington; C. E. Weaver.....	153
LENGTH and character of the earliest interglacial beds; A. P. Coleman.....	71	— Paleozoic section of the Alaska-Yukon boundary; L. D. Burling.....	137
LEPTOMERYX from White River oligocene.....	145	LUCAS, F. A., cited on Imperial mammoth measurements.....	407
LERCH, —, Geological work in Louisiana of.....	173	LUDWIG, R., cited on pillow structure.....	597
LESQUEREUX, L., cited on correlation of Raton formation.....	333	LULL, R. S., elected chairman Paleontological Society meeting.....	129
— Cretaceous floras.....	375	—; Miocene dolphin from California.....	142
LEVERETT, F., Discussion of coastal subsidence by.....	62	—; New accessions to the exhibition series at Yale Museum.....	143
— glacial deposits in Ontario by.....	72	—; New mastodon found in Connecticut.....	143
— preglacial drainage by.....	85	— presided at meeting.....	139, 142
—; Earth-movements in the Minnesota portion of the Lake Agassiz basin during and since the lake occupancy.....	34	LYCKHOLM formation.....	286
LEWIS, J. V., cited on New Jersey trap sheet.....	624	LYELL, C., cited on demarcation between Eocene and Cretaceous.....	321
—, Discussion of bornite by.....	90	— pillow lava.....	634
— New Jersey gneisses by.....	45	—, Geological work in Georgia of.....	174
—; Origin of pillow lavas.....	32, 591	— Louisiana of.....	172
LEWISTON shales.....	285	—, Visits to the Southern States of.....	163
LIEBER, O. M., State Geologist of South Carolina.....	160	LYNCH, LIEUT., Reference to Dead Sea expedition by.....	162
LIMEHOUSE section, Ontario.....	316	MACDONALD, D. F.; Recent earthquakes in Panama and their causes.....	34
LIMESTONE gravel boulders, Flattening by solution of.....	66	MCCALLEY, H., Geological work in Alabama of.....	170
LINCK, G., cited on oolites.....	759	MCCALLIE, S. W., cited on oolitic iron ores.....	769, 772-773
— origin of oolites.....	750	—, Geological work in Georgia by.....	174
LITTLE, GEORGE, Geological work in Georgia by.....	174	MCCONNELL, R. G., cited on Belly River series.....	370
— Mississippi of.....	170	— Macmillan River beds of Alaska.....	202
LIVINGSTON formation of Montana.....	346	— Nasina series of Alaska.....	186
LLOYD, E. R., cited on Cannonball formation.....	339	— rocks of Macmillan River of Alaska.....	198
— geology of Indian reservations.....	350	—, Geological work on Porcupine River of.....	180
LOCKPORT section.....	307	MACDOUGAL, —, cited on Salton Basin terraces.....	562
LOCKYER, W. J. S., cited on cyclonic storms.....	524	MCGEE, W. J., Researches in Coastal Plain geology of.....	177
LOESS, Chart of distribution of.....	575	MACCLESFIELD, England, Reference to deposits in.....	211
—, Mechanical analysis of.....	728	MACLURE, WILLIAM, Geological work in Georgia of.....	173
LOEWINSON-LESSING, F., cited on magmatic differentiation.....	260	— Louisiana of.....	172
LOGAN, —, cited on Cabots Head section, Ontario.....	319	—, President American Geological Society.....	160
— Dundas section, Ontario.....	315	—, Reference to writings of.....	159
— Thorold section, Ontario.....	310	MACTRIDÆ of west coast.....	151
— Hamilton section, Ontario.....	313	MADAGASCAR, Reference to climatic changes in.....	482
LONDON basin, Cretaceous.....	336	MADDEN, A. G., cited on Tindir rocks of Porcupine River.....	188
LONG ISLAND, Marine fossils from.....	242	MÆSTRICHTIEN stage, Reference to.....	321
LOOMIS, F. B., Analysis of the pyrotherium fauna.....	140	MAGDALEN Islands, Glacial drift on.....	84
— cited on dinosaurs.....	401	MAGMATIC differentiation and assimilation in the Adirondack region; W. J. Miller.....	45, 243
—; Restoration of some pyrotherium mammals.....	139	MAINE, Pillow lavas of.....	620
LORD, —, cited on veins of chalcopryrite and galena.....	474	MAMMALIAN fauna of the Pleistocene beds at Manix, in the Mohave Desert region; J. P. Buwalda.....	156
LOUDERBACK, G. D., Discussion of Arizona erosion and deposition by.....	125	MANCAS beds, Flora of the.....	334
— climatic provinces by.....	124		
— Great Basin deformations by.....	122		
— Haywards Rift by.....	123		
— Nevada stibnite by.....	126		

	Page		Page
MANGANESE deposits of Conception and Trinity bays, Newfoundland; N. C. Dale.....	73	MELDRUM, —, cited on cyclones.....	83
MANITOULIN limestone.....	280	— tropical hurricanes.....	494
MANITOWANING section, Ontario.....	320	MEMBERS of the Paleontological Society.....	146
MARCOU, J., Geological work of.....	165	MEMORIAL of T. M. Jackson by J. C. White.....	13
MARCY's survey of the Red River of Louisiana, Reference to.....	165	— W. M. Fontaine by T. L. Wilson.....	6
MARLBORO formation.....	441	MERRIAM, C. HART, cited on barriers to migration of land animals.....	397
MARSH, O. C., cited on Lance fauna.....	391	—, Reference to studies by.....	413, 415
—, Inadequacy of classification of dinosaurs by.....	378	MERRIAM, J. C., cited on Cretaceous-Eocene boundary.....	343
MARTIN, B., appointed representative of Paleontological Society.....	150	—, Correlation of the Tertiary formations of the Pacific coast and basin regions of western United States.....	156
—, Observations on the use of the percentage method in determining the age of Tertiary formations in California.....	152	—, Motion made by.....	151
MARTIN, L.; Submarine topography in Glacier Bay, Alaska.....	88	—, Results of recent work at Rancho La Brea.....	143
MARTINEZ Eocene of California.....	154	—, Terrestrial Oligocene of the basin region and its relation to the marine Oligocene of the Pacific Coast province.....	153
MASSACHUSETTS, Cumberland-Diamond Hill district of.....	75	—, Vertebrate fauna of the Orindan and Slesian formations.....	156
—, Pillow lavas of.....	621	MERRILL, G. P., Reference to writings of.....	159
—, Rhode Island Diamond Hill-Cumberland district.....	435	—, Discussion of coastal subsidence by.....	60
MASTODON find in Connecticut.....	143	—, oolites of Chimney Hill formation by.....	76
MASTODONS, Restoration of.....	142	MERRITT, J. W.; Sedimentary character of garnetiferous hornblende schist, Hanover, New Hampshire.....	75
— the world's series of.....	407-410	MESAVERDE formation.....	345
MATHEWS, E. B., Report of Auditing Committee by.....	49	MESOZOIC mammals, Reference to.....	322
MATTHEW, W. D., Acknowledgments to.....	356	— Pennsylvanian-Orange group of Alaska.....	201
— acted as secretary of meeting.....	139	METEOROLOGICAL hypothesis of climatic changes.....	481
— cited on extension of the definition of Laramie.....	338	MIAMI and Kentucky rivers, Preglacial.....	95
—, Discussion of Mylodont sloths by.....	144	MICHIGAN, Devonian black shale of.....	137
—, Pleistocene cave deposit by.....	142	MICRO-SECTIONS of oolitic structures.....	778-780
—, Pyrotherium mammals.....	140	MIDWAY formation of the Eocene.....	332
—, symposium papers by.....	130	MIGRATION and diastrophism of fauna.....	397
— the Lemuroidea by.....	141	MILFORD granite of Diamond Hill-Cumberland district.....	454
— elected secretary of meeting of Paleontological Society.....	129	MILLER, E. M., Discussion of Kentucky oolites by.....	59
—, Evidence of the Paleocene vertebrate fauna on the Cretaceous-Tertiary problem.....	381	MILLER, G. S., Reference to studies by.....	413, 416
—, Reference to investigations by.....	323	MILLER, W. J., cited on Adirondack rocks.....	248, 251, 256-259
—, symposium paper by.....	130	—, Discussion of Adirondack geology by.....	47
—, Report of progress in the revision of the Lower Eocene faunas.....	144	—, Magmatic differentiation and assimilation in the Adirondack region.....	45-243
MAURITIUS, Reference to climatic changes in.....	482	MILLINGTON, J., Geological work in Mississippi.....	170
MAYA ruins as evidence of climatic changes.....	539	MILODONT sloth of Rancho La Brea.....	143
MAYER, —, cited on demarcation between Tertiary and Eocene.....	321	MINERALS from the ore deposits at Park City, Utah; F. R. Van Horn.....	47
MAZZUOLI, L., cited on pillow structure.....	599	MINNESOTA, Earth-movements in.....	34
MEANDERS in the Connecticut Valley, Glacial.....	232	—, Section at Saint Paul.....	267
MEARS, H. S., Analysis of quartz rock and felsite by.....	473	MINUTES of the Fourth Annual Meeting of the Pacific Coast Section of the Paleontological Society; R. E. Dickinson, Secretary.....	150
— cited on Diamond Hill quartz deposits.....	471	MIocene dolphin from California; R. S. Lull.....	142
MECHANICAL composition of clastic sediments.....	655	— of the Muir syncline.....	154
MECHANICS of formation of arcuate mountains; W. H. Hobbs.....	30	— Washington, Lower.....	153
MEDINA and Cataract formations of the Siluric of New York and Ontario; Charles Schuchert.....	277	MISSISSIPPI embayment, Reference to.....	170
—, Cataract, and Clinton, Contacts between.....	292	—, Geological work in.....	170
— fauna. Fossils of.....	288, 290	MISSOURI, Paleozoic faunas in.....	135
— formation, History of the.....	297	MESOZOIC marine vertebrates, Extension of history of.....	366-367
— Sea, Paleogeography of.....	295	MITCHELL, E., State geologist of North Carolina.....	160
— section.....	306	MODE of formation of certain gneisses in the highlands of New Jersey; C. N. Fenner.....	44
MEHL, M. G., Title of paper by.....	135		
MERGEN, W., cited on origin of oolites.....	753		
MEINZER, —, cited on basin terraces of New Mexico.....	562		

	Page		Page
MOEL Tryfaen, Wales, Reference to deposits found in.....	210-211	NEW MEXICO, Mammal-bearing beds of.....	325
MOHAVE Desert region, Pleistocene fauna of the.....	156	—, Post-Cretaceous floras of.....	334
MOHAWK Valley glacial features.....	209	—, Record of rainfall in.....	535
MONGOLIA, Inclosed lakes of.....	563	—, Red beds of.....	81
MONTANA beds, Flora of the.....	332	—, Reference to dinosaur fauna of.....	323
—, Conglomerate of.....	346	NEW point in the geology of the Adirondacks; J. F. Kemp.....	47
—, Cretaceous-Eocene correlation in.....	355	— titanotheres from Uinta formation of Utah; O. A. Peterson.....	144
—, epoch, Crustal oscillations during the.....	344	NEW YORK, Devonian black shale of.....	137
—, Oscillating movements in.....	346	—, Medina, Cataract formations of.....	277
—, Glacial erosion in.....	86	—, Reference to climatic changes in.....	482
—, Lake Missoula of.....	87	—, Serpentine of Staten Island.....	87
—, Livingston formation of.....	346	—, Siluric sections in.....	304-320
MONTREY series, Fauna of the.....	151	—, Sketch map of eastern central.....	69
MONTIEN beds.....	336	NIAGARA gorge section.....	308
— deposits.....	342	—, Time measures in the.....	35
— stage, Reference to.....	321	NICHOLSON, —, cited on oolitic rock.....	748
MOODY, W. L., Inquiries by.....	125	NIOBARRA limestone.....	345
MOOK, C. C.; Notes on <i>Camarosaurus cope</i>	143	NOMENCLATURE of minerals: A. F. Rogers.....	124
MOORE, —, Reference to geological work of.....	166	NORTH AMERICAN Cretaceous and Eocene, Contact between.....	342
MOORE, E. S., cited on oolites.....	761-762	NORTH CAROLINA, Geological survey created in.....	160
—, Oolitic and pisolitic barite from the Saratoga oil field of Texas.....	77	NORTH DAKOTA, Lance formation of.....	348
MORGAN, C. L., cited on pillow lavas.....	605	NORTH Park, Plant-bearing beds of.....	333
MORLEY, E. W., Analysis of Adirondack rocks by.....	251	NOTE on the American Triassic genus <i>Placerias lucas</i>	141
MORTON, —, Geological work by.....	160	NOTES on <i>Camarosaurus cope</i> ; C. C. Mook.....	143
—, — in Georgia by.....	173		
MOUNTING of rock and fossil specimens with sulphur; C. A. Reed.....	136	OBSERVATIONS on the use of the percentage method in determining the age of Tertiary formations in California; B. Martin.....	152
MUIR Glacier, Retreat of.....	209	OCCURRENCE of free gold in granodiorite of Siskiyou County of California; A. F. Rogers and E. S. Boundey.....	124
— syncline, Miocene oysters of the.....	154	—, glacial drift on the Magdalena Islands; J. W. Goldthwait.....	84
MURGOCI, G., cited on climatic pulsations.....	533	—, mammalian remains at Rancho La Brea; R. C. Stroner.....	156
MURIE, —, cited on anatomy of horse and tapir.....	406	—, stibnite and metastibnite at Steamboat Springs, Nevada; J. C. Jones.....	126
MURRAY, —, cited on oolites.....	759	OFFICERS and members of the Paleontological Society, Election of.....	133
"MUTATIONS of Waagen".....	411	—, Correspondents, and Fellows of the Geological Society.....	107
		—, Election of.....	5
NARRAGANSETT series, Divisions of.....	447	—, for 1914, List of members selected as.....	5
NATURE of the later deformations in certain ranges of the great basin; C. L. Baker.....	122	—, of the Cordilleran Section.....	125
NAUMANN, C. F., cited on origin of pillow lavas.....	637	—, the Pacific Coast Section of the Paleontological Society.....	151
—, — pillow lavas.....	595-596	OGILVIE, I. H., cited on Adirondack rocks.....	248
NANSEN, F., cited on temperature variations in Atlantic current.....	493	OHIO, Devonian black shale of.....	137
NEVADA, Stibnite at Steamboat Springs.....	126	OJO Alamo beds correlated with the Judith River.....	380
NEW accessions to the Exhibition series at Yale Museum; R. S. Lull.....	143	—, —, Fossils of the.....	379-380
NEWBERRY, J. S., cited on oolitic iron ores.....	770	OKLAHOMA, Chimney Hill formation of.....	75
NEW BRUNSWICK, Pillow lava of.....	611	OLIGOCENE and Eocene of California, Relations of.....	153
NEWCOMB, S., cited on solar heat.....	486, 499	— (?) of Oregon.....	154
NEWFOUNDLAND, Algonkian rocks of.....	40	—, the basin region and its relation to Oligocene of Pacific Coast province.....	153
—, Cambrian and Ordovician faunas of.....	138	—, Skeletons of leptomeryx from White River.....	145
—, Manganese deposits of.....	73	OLMSTEAD, D., made State Geologist of North Carolina.....	160
—, Pillow lavas of.....	611	ONTARIO, Canada, Siluric sections in.....	308-320
—, Wabana iron ores of.....	74	—, Contact of Cataract formation in.....	287
NEW HAMPSHIRE, Garnetiferous hornblende schist of.....	75	—, Glacial deposits in.....	71
NEW JERSEY gneisses, Mode of formation of.....	44	—, Medina and Cataract formations of.....	277
—, Pillow lavas of.....	623	—, Pillow lava of.....	611
NEWLAND, D. H., cited on oolitic iron ore.....	768	—, region, Postglacial deformation of the.....	65
NEW mastodon find in Connecticut; R. S. Lull.....	143	—, Silurian system of.....	40
— method of restoring eotitanops and brontotherium; H. F. Osborn.....	140, 406	—, Temiskamite from.....	76
NEW MEXICO coal-bearing strata, Deposition of.....	345		
—, Cretaceous Eocene correlation in.....	355		
—, "Laramie?" Puerco and Torrejon of.....	138		

	Page		Page
OOLITES and oolitic structures, Micro-		PALEOCENE, Use of the term.....	381
— sections of.....	778-780	— vertebrate fauna as evidence on the	
— texture, Bibliography of.....	774-777	— Cretaceous-Tertiary problem.....	381
— the oolitic texture, Origin of.....	58	PALEOGEOGRAPHIC maps of North Amer-	
— of the Chimney Hill formation, Okla-		— ica.....	136
— homa; C. A. Reeds.....	75	PALEOGEOGRAPHY of Medina, Cataract,	
— Pennsylvania.....	760	— and Brassfield seas.....	295
— Analyses of.....	767	PALESTINE, Reference to climate of.....	536
— Origin of.....	745	PALEOZOIC cephalopods, Restoration of.....	136
OOLITIC and pisolitic barite from the		— delta deposit of Devonian black shale.....	137
Saratoga oil field of Texas; E. S.		— faunas in southwestern Missouri.....	135
Moore.....	77	— section of Alaska-Yukon boundary.....	13
— iron ore.....	768	PALMER, C. Genesis of glauconite.....	91
— textures in rock, Origin of.....	745	PANAMA earthquakes and their causes.....	34
ORANGE group of Alaska.....	201	PARISIAN basin, Cretaceous and Ter-	
ORDOVICIAN and Siluric systems, Con-		— tiary systems of.....	336
— tacts between [plate 13].....	286	— Reference to.....	341, 342
— Cambrian faunas of Newfound-		PARK City minerals.....	47
— land.....	138	PARKS, E. M., cited on geology of In-	
— brachiopoda.....	421	— dian reservations.....	350
— List of.....	424-427	PARKS, W. A., cited on Cataract fauna.....	281
— Comparison of lithologic, strati-		— Cataract section, Ontario.....	317
— graphic, and geographic range of.....	428	— Clinton formation.....	279
— conglomerates of the Galena-Trenton		— Grimsby section, Ontario.....	310
— series.....	265	— Hamilton section, Ontario.....	313
OREGON, Oligocene (?) of.....	154	PARMELEE, C. W., Discussion of physi-	
ORIGIN of dolomite; F. M. Van Tuyl.....	66	— cal-chemical system by.....	92
— oolites and the oolitic texture in		PARSONS, —, cited on anatomy of	
rocks; T. C. Brown.....	58-745	— horse and tapir.....	406
— pillow lavas; J. V. Lewis.....	32-591	PASKAPOO fauna, Characters of the.....	388
ORINDAN and Siestan formations, Fauna		— formation, Fossils of the.....	371-373
— of.....	156	PAWTUCKET formation of Narragansett	
OSBORN, H. F., cited on Lance fauna.....	391	— series.....	447
— Close of the Cretaceous and opening		PEACH, B. N., cited on pillow lava.....	606
— of Eocene time in North America.....	321	PEALE, A. C., cited on the Judith River	
— Discussion of Pleistocene cave de-		— formation.....	393
— posits by.....	142	— — the Laramie.....	338
— symposium papers by.....	130	— — relation of Upper and Lower	
— the lemuroidea.....	141	— Laramie.....	328
— Final results in the phylogeny of		PECK, C., Geological work in Louisiana	
the titanotheres.....	139	— of.....	172
— New method of restoring eotitanops		PENCK, A., cited on climatic changes.....	540
and brontotherium.....	140, 406	PENNSYLVANIA, Analyses of oolites from	
— Paper of B. Brown presented by.....	355	— Glacial ice-dam in the Allegheny	
— E. Douglass read by.....	417	— River.....	84
— Recent results in the phylogeny of		— topography in [plate 9].....	215, 216
the titanotheres.....	403	— (Lower) igneous rocks of Diamond	
— Rectigradations and allometrons in		— Hill-Cumberland district.....	461-462
relation to the conceptions of the		— (Middle) igneous rock, Diamond	
"mutations of Waagen" of species,		— Hill-Cumberland district.....	463-474
genera, and phyla.....	142, 411	PENNSYLVANIA, Oolites of.....	760
— Reference to symposium paper of.....	130	— rocks, Diamond Hill-Cumberland dis-	
— Restoration of the world series of		— trict.....	446
elephants and mastodons.....	142, 407-410	PERMIAN glacial periods, Reference to.....	589
OSGOOD, —, Reference to studies by.....	413	— glaciation.....	578-588
OWEN, D. D., Geological work of.....	166	PERMO-CARBONIFEROUS beds of Texas,	
OWEN Sound section, Ontario.....	319	— Climatic oscillations in.....	41
OYSTERS of the Miocene of the Muir		— (?) conglomerate of Alaska.....	199
syncline.....	154	PERRY, J. H., Analysis of porphyry by.....	469
OX-BOWS in the Connecticut Valley,		— Analysis of riebeckite-porphyry by.....	466
Glacial.....	232	— cited on Bellingham series.....	449
		— granite dike.....	468
		— Milford granite.....	454
		— Quincy granite.....	465
		— porphyry.....	463
		— Mapping of quartz diorite area by.....	452
		— Work in the Diamond Hill-Cumber-	
		— land district by.....	438-441
PACIFIC coast and basin regions, Corre-		PERU, Reference to climatic changes in.....	482
— lation of Tertiary formations of.....	156	PETERSON, O. A.; New titanotheres from	
— province, Oligocene of.....	153	— Uinta formation of Utah.....	144
— Section of the Paleontological So-		— cited on Uinta group.....	418
— ciety, Fourth Annual Meeting of		PETROGRAPHIC microscope, Polarized	
the.....	150	— skylight and the.....	120
— Reference to.....	123	— province, Method of representing	
PACKARD, E.; Some west coast matridae		— chemical relations of a.....	43
PAHOEHOE lava, Chronological table of.....	629	PETROGRAPHY of the rocks of Diamond	
— Formation of.....	639	— Hill-Cumberland district.....	449
PAIGE, S., Discussion of magmatic dif-		PETROLOGY of the Adirondack region.....	244
— ferentiation by.....	46	PETRUNKEVITCH, ALEX., elected to Pale-	
PALACHE, C., cited on Diamond Hill		— ontological Society.....	134
quartz deposits.....	472		
PALEOCENE fauna, Typical.....	382		
— faunas.....	382-385		
— formations in Europe, Reference to.....	322		

	Page		Page
PETERSSON, O., cited on connection between hydrographic and meteorologic phenomena.....	550-552	PRINDLE, L. M., cited on Devonian limestone of Alaska.....	193
—, Sun-spot hypothesis of.....	552	—, Geological work in Alaska by.....	180
PHILLIPS, J. A., cited on oolitic iron ore.....	770	PRIOR, G. T., cited on pillow lavas.....	604
PHILLIPS, —, Reference to geological work of.....	166	PROCEEDINGS of the Fifth Annual Meeting of the Paleontological Society, held at Princeton, New Jersey, December 31, 1913, and January 1, 1914; R. S. Bassler, Secretary.....	127
PHILOGENY of the titanotheres.....	403	— Fourteenth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, April 11 and 12, 1913; G. D. Louderback, Secretary.....	119
PHYLETIC relationship of the lemuroides; W. K. Gregory.....	141	— Twenty-sixth Annual Meeting of the Geological Society of America, held at Princeton, New Jersey, December 30 and 31, 1913, and January 1, 1914; E. O. Hovey, Secretary.....	1
PHYLOGENETIC development of the <i>Heactinellid dictyosponges</i> as indicated by the ontogeny of an Upper Devonian species; J. M. Clarke.....	138	PUBLICATION rules of Geological Society.....	101
PHYSICAL-CHEMICAL system, lime-alumina-silica, and its geological significance; F. E. Wright and G. A. Rankin.....	92	PURDUE, A. H., Discussion of Colorado glaciation by.....	32
PHYSIOGRAPHIC features of the Haywards Rift; D. M. Durst.....	123	—, Geological work in Arkansas of.....	167
— relations of serpentine, with special reference to the serpentine stock of Staten Island, New York; W. O. Crosby.....	87	— Tennessee of.....	168
PIERRE-EDMONTON contact.....	368	PUERCO fauna compared with other faunas.....	387
—, Near-shore phase of the.....	326	— formation.....	338, 382
PILLOW lavas, Chronological table of.....	629-633	— without equivalent in Europe.....	396
—, Distribution of.....	595	PYROTHERIUM fauna, Analysis of.....	140
—, Origin of.....	32, 591	— mammals, Restoration of.....	139
PIONEERS in Gulf Coastal Plain geology; E. A. Smith.....	157	PYROXENE-BEARING artificial melts, Crystallization of.....	91
PISHEL, M. A., cited on geology of Indian reservations.....	350	QUATERNARY deposits of Alaska.....	202
PLATANIA, G., cited on globular basalt.....	600	— fauna compared with other faunas.....	387
—, origin of pillow lavas.....	653	QUANTITATIVE classification, Effusive and intrusive in the.....	43
PLEISTOCENE beds in the Mohave Desert region.....	156	QUARTZ, Changes caused by rise of temperature in.....	44
— glacial period, Reference to.....	589	— deposits of Diamond Hill.....	471
— marine submergence of the Connecticut and Hudson valleys; H. L. Fairchild.....	63, 219	— diorite of Diamond Hill-Cumberland district.....	452
POCY, —, cited on tropical hurricanes.....	494	QUEENSTON shales.....	285
POGUE, J. E., Discussion of fornite by.....	90	QUINCY granite, Analysis of.....	466
—, physical-chemical system by.....	92	RAINFALL in New Mexico and Arizona, Records of.....	535
POLARIZED skylight and the petrographic microscope; U. S. T. Smith.....	120	— the United States, Records of.....	538
PONDVILLE arkoses of Narragansett series.....	447	RAISIN, C. A., cited on origin of pillow lavas.....	639
POPE, JOHN, Reference to survey work by.....	165	—, spheroidal rocks.....	601
POST-CRETACEOUS floras.....	334	RANCHO LA BREA, Fauna of.....	155
POSTGLACIAL deformation of the Ontario region.....	65	—, Mammalian remains at.....	156
POST-PERMIAN diabase dikes in Diamond Hill-Cumberland district.....	474	RANGE of land vertebrates in typical American formations.....	387
POWELL, CAPTAIN, Reference to expedition to Florida.....	162	RANSOME, F. L., cited on origin of pillow lavas.....	618, 639, 653
POWELL, J. W., Reference to.....	177	RATON formation.....	329
—, Use of name "Uinta" by.....	417	—, Correlation of the.....	334
POWERS, S., and C. H. Warren; Geology of the Diamond Hill-Cumberland district in Rhode Island-Massachusetts.....	435	—, Fossil flora of the.....	331-333
PRATT, J. H., State geologist of North Carolina.....	160	READ, T. T., Discussion of Park City minerals by.....	47
PRE-CAMBRIAN igneous rocks of Diamond Hill-Cumberland district.....	449-452	RECENT earthquakes in Panama and their causes; D. F. MacDonald.....	34
— metamorphic rocks of Alaska.....	184	— results in the phylogeny of the titanotheres; H. F. Osborn.....	403
— rocks; Blackstone series of Diamond Hill-Cumberland district.....	440	RECONNAISSANCE of the Algonkian rocks of south and east Newfoundland; A. F. Buddington.....	40
— sedimentary rocks of Alaska.....	187	RECTIGRADATIONS and allometrons in relation to the conception of the "mutations of Waagen" of species, genera, and phyla; H. F. Osborn.....	142, 411
— unconformity in Vermont.....	39	RED beds of New Mexico.....	81
PRECIPITATION, Historic changes in.....	542	— Deer River canyon, Horizontal geological section of.....	363
PRECISE leveling and the problem of coastal subsidence; D. W. Johnson.....	59	—, Generalized section of the Bad Lands of.....	364-365
PREGLACIAL Miami and Kentucky rivers; N. M. Fenneman.....	85		

	Page		Page
RED Deer River geologic section...	359-360	RIGGS, E. S., cited on Uinta group...	418
— section, Summary of the...	371-379	—; Group of twenty-six associated skeletons of Leptomyx from the White River Oligocene...	145
REED, W. G.; Climatic provinces of the United States west of the Rockies...	124	ROBBINS, —, cited on climatic changes...	548
—; Variations in rainfall in California...	121	ROCHESTER section...	304
REEDS, C. A., Discussion of oolites by...	59	ROCKY Mountain region, Cretaceous-Tertiary boundary in the...	325
—, Discussion of restoration of Paleozoic cephalopods by...	136	ROEMER, F., Geological work in Texas of...	164
—; Mounting of rock and fossil specimens with sulphur...	136	ROGERS, A. F., and E. S. BOUNDEY; Occurrence of free gold in granodiorite of Siskiyou County, California...	124
—; Oolites of the Chimney Hill formation, Oklahoma...	75	—, Discussion of Nevada stibnite by...	126
REGISTER of the Berkeley meeting...	126	—; Nomenclature of minerals...	124
— — Paleontological Society...	145	ROGERS, A. W., cited on Carboniferous conglomerate of Africa...	201
— — Princeton meeting...	105	ROTH, —, cited on dinosaurs...	401
REID, C., cited on origin of pillow lavas...	638	ROTHPLETZ, A., cited on origin of oolites...	749, 753, 754
— pillow lava...	604	— — — pillow lavas...	637
REID, H. F., Discussion of Glacier Bay topography by...	89	— — — pillow structure...	596-597
— — the movements of glaciers by...	36	ROWE, J. P., cited on barite selenite from Montana...	79
—; Earthquake sea waves...	33	ROYCE, W. A., Analysis of Pennsylvania oolitic limestone by...	758
RELATIONS of the American pelycosaurs to the South African dinocephalians: R. Broom...	143	RUEDEMANN, R.; An alternative explanation of the origin of the Saratoga mineral waters...	38
REPORT of Auditing Committee...	49	—, Discussion of Alaska Paleozoic section by...	137
— Committee on Geological Nomenclature...	49	— — new paleogeographic maps by...	136
— — Photographs...	49	—, Report on Alaskan graptolites by...	194
— Council of Paleontological Society...	130	—; Restoration of Paleozoic cephalopods...	136
— progress in the revision of the Lower Eocene faunas; W. D. Matthew...	144	RUFFIN, E., Geological work of...	168
— the Council...	51	—, State Geologist of South Carolina...	160
— Editor...	56	RUSSELL, G. S., cited on earthquake seawaves...	34
— Secretary...	51	RUSSELL, I. C., cited on Albert Lake terraces...	560
— Treasurer...	53	— — bitumen of New Jersey...	627
RESISTANT surfaces developed by erosion and deposition in the arid and semi-arid regions of Arizona; C. F. Tolman, Jr...	125	— — Mono Basin terraces...	562
RESTORATION of Paleozoic cephalopods; R. Ruedemann...	136	— — New Jersey trap sheet...	623
— some pyrotherium mammals; F. B. Loomis...	139	— — origin of pillow lavas...	637, 640, 642
— the world series of elephants and mastodons; H. F. Osborn...	142, 407-410	— — pillow lava...	617
RESULTS of recent work at Rancho La Brea; J. C. Merriam...	143	RUSSIA, Reference to climatic changes in...	482
REUNING, E., cited on origin of pillow lavas...	638, 653	RUTOT, —, cited on the Montien of Belgium...	394
— — origin of pillow structure...	636	SAFFORD, J. M., Comment on Troost's reports by...	161
— pillow structure...	598	—, Geological work in Tennessee of...	167
REVIEW of the early history of the Society; H. L. Fairchild...	17	—, Work on cotton reports of...	176
— — formation of geological societies in the United States; N. H. Winchell...	27	SAINT PAUL, Minnesota, Section at...	267
REYNOLDS, S. H., cited on pillow lavas...	605, 608	SALISBURY, R. D., cited on Delaware terraces...	86
RHODE ISLAND, Cumberland-Diamond Hill district of...	75	—, Discussion of earth-movement in Minnesota by...	35
—, Massachusetts Diamond Hill-Cumberland district...	435	— — intraformational corrugation...	37
RHONE Glacier, Reference to decline of...	491	— — Ontario glaciation by...	72
RICE, W. N., Discussion of submergence of Connecticut and Hudson valleys...	64	— — Red beds by...	82
RICH, J. L.; Divergent ice-flow on the plateau northeast of the Catskill Mountains as revealed by ice-molded topography...	68	—, Meeting of the First Section called to order by...	65
RICHARDSON, J., cited on non-glaciation of Magdalen Islands...	84	—, Paleozoic glaciation discussed by...	31
RICHMONDIAN formation...	286	SANDS containing magnetite, Mechanical analysis of...	727
RIEBECKITE-EGIRITE granite, Analysis of...	466	SAN JOAQUIN Valley, Geology of the...	123
— of Diamond Hill-Cumberland district...	463	SAN LORENZO Oligocene...	153
— bearing granite porphyry...	467	SAN PABLO, Echinoderms of the...	152
RIES, H., acted as secretary for Group C, Third Section...	43	— series, Fauna of the...	152
		SANTA MONICA Mountains, Vaqueros of the...	153
		SARATOGA oil field, Barite from...	77
		— Springs, Exposure of the fault escarpment at...	38
		—, Origin of mineral waters of...	38
		SARDESON, F. W.; Characteristics of a corrosion conglomerate...	39, 265
		SAXONY, Pillow lavas in...	595

	Page		Page
SCHERZER, W. H., cited on origin of oolites	753	SIESTAN and Orindan formations, Fauna of	156
SCHLEY, Governor, Recommendation for Georgia Geological Survey by	173	SILURIAN calcareous algæ	137
SCHMALZ, —, cited on anatomy of horse and tapir	406	—system of southwestern Ontario	40
SCHOEPP, J. D., Coastal Plain investigations by	158	SILURIC and Ordovician systems, Contacts between [plate 13]	286
SCHOFIELD, S. J., cited on belt terrane of British Columbia	189	—, Medina, and Cataract formations of the	277
SCHOTT, —, Geological work in Texas of	165	—sections from Rochester to Lake Huron	304-320
SCHUCHERT, CHARLES; Chart of glaciation and land distribution	586	SIMPSON, —, Fossils secured near the house of	367
—, cited on Cambrian brachiopoda	421	SINCLAIR, W. J., cited on Ojo Alamo beds	379
—, correlation of the Medina with other formations	292	—, —, Nacimiento terrane	382
—, reference to paleogeographic map by	353	—, —, Puerco mammals	338
—, —, the Cretaceous sea	335	—, —, Puerco-Torreon stratigraphy	401
—, —, volcanic hypothesis of climatic changes	544	—, —, "Laramie?" Puerco and Torreon in the San Juan Basin, New Mexico	138
—, Discussion of Alaska Paleozoic section by	137	—, Reference to investigations by	323
—, —, Colorado glaciation by	32	—, —, studies of Eocene faunas by	144
—, —, corrosion conglomerate by	39	—, —, symposium paper by	130
—, —, new paleogeographic maps by	136	SKELTON of Notharctus, an Eocene lemuroid; W. K. Gregory	141
—, —, Paleozoic faunas by	135	SLOAN, E., State Geologist of South Carolina	160
—, —, symposium papers by	130	SMITH, E. A., cited on life of Mr. Tuomey	169
—, Medina and Cataract formations of the Siluric of New York and Ontario	277	—, Geological work in Alabama of	170
SCOTLAND, Pillow lavas in	606	—, Delivery of presidential address by	48
SCOTT, W. B., Discussion of Pyrotherium fauna by	140	—, Meeting of December 31 called to order by	48
—, —, Pyrotherium mammals	139	—, —, First Section called to order by	84
—, —, titanotheres by	139	—, —, Group B, Second Section, called to order by	39
—, Reference to address by	5	—, —, Opening of meeting by	4
SEA waves caused by earthquakes	33	—, —, Pioneers in Gulf Coastal Plain geology	157
SECRETARY'S report of the Paleontological Society	131	—, Reference to speech at dinner by	80
SECTION at Saint Paul, Minnesota	267	—, Work on cotton reports of	176
—, of Bad Lands of the Red Deer River	364-365	SMITH, G. O., cited on amygdaloidal diabases	620
—, —, the Edmonton-Pierre contact	369	—, Letter concerning formation names by	50
—, —, Red Deer River canyon	363	—, Reference to speech at dinner by	80
—, —, the Red River, Summary of the geologic	371-379	—, cited on effects of weather on vegetal growth	529
SECTIONS illustrating the lower part of the Silurian system of southwestern Ontario; M. Y. Williams	40	SMITH, W. S. T., elected Councilor of Cordilleran Section	125
—, of the Siluric from Rochester to Lake Huron	304-320	—, Polarized skylight and the petrographic microscope	120
—, through Copper Mine Hill and Cumberland Hill	469, 471	—, Some graphic methods for the solution of geologic problems	120
SEDIMENTARY character of garnetiferous hornblende schist, Hanover, New Hampshire; J. W. Merritt	75	SMITHFIELD limestones	440, 443
SEDIMENTS, Composition of clastic	655	SMITHSONIAN Institution, Reference to investigation of solar heat by	485
—, Differences between water and wind	740	SMYTH, C. H., Jr., Acknowledgments to — cited on Adirondack rocks	244, 254
SEDIMENTATION of the interior province	343	SMYTH, H. L., cited on Marquette greenstones	614
—, Laws governing	732-737	SPARNACIAN and Ypresian equivalent to Wasatch	396
SEELEY, H. G., cited on oolitic texture	749	SPENCER, J. W.; Cause of the postglacial deformation of the Ontario region	65
SERPENTINE of Staten Island	87	—, cited on Hamilton section, Ontario	313
—, veins of Diamond Hill-Cumberland district	451	—, —, Dundas section, Ontario	315
SELMA chalk	332	—, Discussion of coastal subsidence by	60-61
SELLARDS, E. H., Geological work in Florida of	176	—, —, earth-movements in Minnesota by	35
SHALER, N. S., cited on Blackstone series	443-444	—, —, submergence of Connecticut and Hudson valleys	64
—, Work in Diamond Hill-Cumberland district by	438	—, —, time measures in the Niagara gorge by	36
SHELDONVILLE quartz vein	473	—, Geological work in Georgia of	174
SHEPARD, E. S., cited on origin of pillow lavas	643	SPOERER'S law of shifting sun-spots, Reference to	510
SHEPARD, —, Geological work in Georgia of	173	SPURR, J. E., cited on Birch Creek series of Alaska	186
SHUMARD, B. F., Geological work of	165		
SHUMARD, G. G., Geological work of	165		

	Page
SOKOTRA granite, Analysis of.....	466
SOLAR hypothesis of climatic changes; E. Huntington.....	82, 477-484
SOMBER beds.....	325
SOME contact metamorphic minerals in crystalline limestone at Crestmore, near Riverside, California; A. S. Eakle.....	125
—graphic methods for the solution of geologic problems; W. S. T. Smith.....	120
—historical evidence of coastal subsi- dence in New England; C. A. Davis.....	61
—new paleogeographic maps of North America; A. W. Grabau.....	136
—observations of the volcano Kilauea in action; A. L. Day.....	80
—physical features of Hawver Cave; J. C. Hawver.....	155
—west coast mactridæ; E. Packard.....	151
SORBY, H. C., cited on origin of oolites.....	750
SOUTH CAROLINA, Creation of Geological Survey of.....	160
—, Geological work in.....	168
SOUTH DAKOTA, Lance formation of.....	348
STANLEY-BROWN, J.; History of the Bul- letin.....	24
—, Reference to speech at dinner by.....	80
STANTON, T. W., Acknowledgments to.....	356
—; Boundary between Cretaceous and Tertiary in North America as in- dicated by stratigraphy and inverte- brate faunas.....	341
—cited on fossils of Edmonton forma- tion.....	365
—Lance flora.....	396
—Mesozoic fossils of Alaska.....	202
—, Discussion of symposium papers by.....	130
—, Identification of fossils from the Edmonton formation by.....	375
—Red Deer River fossils by.....	362
—, Reference to symposium paper of.....	130
—investigations by.....	323
STAPLETON, M. J., Fossil locality near ranch house of.....	370
STEPHENSON, —, Geological work in Georgia of.....	174
STEPHENSON, L. W., cited on Creta- ceous-Eocene contact.....	343
—hiatus between Cretaceous and Tertiary.....	332
STERNBERG, C. H., cited on Judith River fauna.....	394
STEVENSON, J. J.; Events leading up to the organization of the Geological Society of America.....	15
STEWART, M. N., cited on relation of precipitation to tree growth.....	529
STIBNITE and metastibnite of Nevada.....	126
STOCK, C.; Hawver Cave: its Pleisto- cene fauna.....	155
—; Systematic position of the Milodont sloths from Rancho La Brea.....	143
STONE, R. W.; Glacial Lake Missoula.....	87
—cited, on Livingston formation of Montana.....	346
—stratigraphic relations of Liv- ingston formation.....	346
STONY Creek section, Ontario.....	311
STORM belt of the United States, Chart of.....	570
—record in Europe.....	499
—tracks in Europe, Chart of.....	500
—the United States, Chart of.....	498
STOSE, G. W., cited on edgewise con- glomerate.....	275
STRAHAN, A., cited on pillow lava.....	605
STRATIGRAPHY of Red beds of New Mex- ico; N. H. Darton.....	81
STRENG, A., cited on pillow structure.....	598
STRONER, R. C.; Occurrence of mam- malian remains at Rancho La Brea.....	156

	Page
STRUCTURE and affinities of the Multi- tuberculata; R. Broom.....	140
SUBLACUSTRINE glacial erosion in Mon- tana; W. M. Davis.....	86
SUBMARINE topography of Glacier Bay, Alaska; L. Martin.....	88
SULFOMINERALS' relation to bornite.....	90
SUNDIUS, N., cited on pillow lavas.....	609
SUN-SPOT cycles, Chart of.....	554
—hypothesis of Petterson.....	552
SUN-SPOTS, Effect on storminess.....	545-546
—, Nature of.....	555
SWEDEN, Pillow lavas in.....	609
—, Reference to glacial geology of.....	213
SYMPOSIUM on the close of the Creta- ceous and opening of Eocene time in North America.....	130
SYRIA, Reference to climatic changes in.....	529
SYSTEMATIC position of the Milodont sloths from Rancho La Brea; C. Stock.....	143
TAFF, J. A., Discussion of Washington coal-bearing Eocene by.....	122
TAIT, CHARLES, Reference to Eocene shells collected by.....	161
TAYLOR, F. B., cited on Medina forma- tion.....	287
—, Discussion of deformation of the On- tario region by.....	66
—Ontario glaciation by.....	73
—, Time measures in the Niagara gorge and their application to Great Lake history.....	35
TAYLOR, W. P., Reference to description of antelopes by.....	155
TEALL, J. J. H., cited on pillow lava.....	603, 606
—spheroidal greenstones.....	635
TEMISKAMITE, A new nickel arsenide from Ontario; T. L. Walker.....	76
TEMPERATURE anomalies for various de- grees of cloudiness, Chart of.....	583
TENNESSEE, Geological Survey of.....	161
—work in.....	167
TERRACES, Glacial.....	227
—in Delaware.....	86
TERRESTRIAL Oligocene of the basin re- gion and its relation to the marine Oligocene of the Pacific Coast prov- ince; J. C. Merriam.....	153
TERTIARY and Cretaceous, Correlated with the European succession.....	394
—in North America, Boundary between.....	341
—of California, Relation between.....	152
—periods, Division between.....	398
—climate.....	375
—Cretaceous boundary in the Rocky Mountain region.....	325
—problem, Evidence of the Paleo- cene-vertebrate fauna on the.....	381
—(early) and late Cretaceous forma- tions, Correlations of.....	393
—formations in California, Method of determining age of.....	152
—, Occurrence of dinosaurs in.....	400
—of Pacific coast and basin regions, Correlation of.....	156
—glaciation in Colorado.....	31
—(later) fauna compared with other faunas.....	387
TEXAS, Barite from the Saratoga oil field of.....	77
—, Climatic oscillations in the Permo- Carboniferous beds of.....	41
—, Geological surveys and studies in.....	164
THANÉTIAN beds of France and Belgium.....	323
—equivalent to Torrejon.....	395
—time, Reference to fossils of the.....	322

	Page		Page
THE solar hypothesis of climatic changes; E. Huntington.....	477	UNITED STATES, Effect of sun-spots on storminess in.....	545-549
THOMAS, H. H., cited on pillow lava..	603	—, Pillow lavas of.....	612
THOMASSY, R., Geological work in Louisiana of.....	172	—, Records of rainfall in various States of.....	538
THOMSON, J., cited on origin of pillow lavas.....	638	UPHAM, WARREN, cited on Connecticut Valley terraces.....	222
—, prismatic jointing.....	634	—, Lake Agassiz.....	34
THOROLD section, Ontario.....	310	—, shoreline of Lake Agassiz.....	209
TILL, Mechanical analysis of.....	692	UPPER Laramie beds.....	325
TIME measures in the Niagara gorge and their application to Great Lake history; F. B. Taylor.....	35	USE of crinoid arms in studies of phylogeny; E. Wood.....	135
— scale, The European.....	335	USSHER, W. A. E., cited on pillow lava.....	604
TINDIR groups of Alaska.....	187	UTAH, Coal-bearing formations in.....	345
TITANOTHERES from Uinta formation of.....	144	—, Mesaverde formation in.....	345
—, Phylogeny of the.....	139, 403	—, Minerals from the ore deposits at Park City.....	47
TOLMAN, C. F., JR., elected as chairman of Section.....	126	—, Uinta formation of.....	144
—; Resistant surfaces developed by erosion and deposition in the arid and semi-arid regions of Arizona.....	125	VAN HISE, C. R., cited on belt terrane of British Columbia.....	189
TORONTO, Don River glacial deposits near.....	205	— cited on magmatic assimilation.....	261
—, Glacial deposits in.....	71	—, origin of pillow lavas.....	638
TORREJON fauna compared with other faunas.....	387	—, pillow lavas.....	616
— formation.....	382	—, Wisconsin volcanic rocks.....	253
TORREY, J., JR.; Analysis of Pennsylvania oolites by.....	767	VAN HORN, F. R., Acted as secretary of Third Section.....	73, 90
— cited on oolites.....	760-761	—, Discussion of fornite by.....	91
TREASURER'S report of the Paleontological Society.....	132	—, Minerals from the ore deposits at Park City, Utah.....	47
TREE growth, Effect of climate on.....	495	VAN INGEN, G., A. O. Hayes introduced by.....	74
TRIASSIC genus <i>Placrias lucas</i> , Note on.....	141	—; Cambrian and Ordovician faunas of southeastern Newfoundland.....	138
— limestones of California, Fauna of the.....	155	—, N. C. Dale introduced by.....	73
TRICERATOPS zone.....	356	—, Vote of thanks to.....	84
TRINITY Bay, Mangane deposits of.....	73	VAN RENSSSELAER, STEPHEN, Reference to.....	297
TRINUCLEUS beds of Sweden.....	286	VAN TUYL, F. M.; Origin of dolomite.....	66
TROOST, G., Geological work of.....	160	VANUXEM, LARDNER, cited on Cayuga sandstone.....	287
—, State geologist of Tennessee.....	161	—, Medina formation.....	285, 286, 303
TURNER, H. W., Discussion of California rainfall by.....	121	—, Niagara formation.....	287
—, Discussion of Coast Range glaciation by.....	121	—, Oswego sandstone.....	287
—, Discussion of Great Basin deformations by.....	122	—, Geological work of.....	160
TUOMEY, M., Geological work in Florida of.....	174	—, Influence on James Hall of.....	300
—, State geologist of South Carolina.....	160	—, State Geologist of South Carolina.....	160
TWENHOFEL, W. H., cited on correlations of the Medina with other formations.....	292	Vaqueros of the Santa Monica Mountains of southern California.....	153
TWITCHELL, M. W., State Geologist of South Carolina.....	161	VARIATIONS in rainfall in California; W. G. Reed.....	121
TYRRELL, J. B., cited on Cretaceous strata.....	363	VAUGHAN, T. W., cited on origin of oolites.....	752
—, Paskapoo formation.....	361	—, Discussion of Bahama and Florida oolites by.....	59
—, Wisconsin glaciation.....	72	—, corrosion conglomerate by.....	39
UDDEN, J. A.; Flattening of limestone gravel boulders by solution.....	66	—; Geological history of the Florida coral-reef tract and comparisons with other coral-reef areas.....	41
—; Mechanical composition of clastic sediments.....	655	—, Introduction of C. Palmer by.....	91
UINTA formation, Geology of the.....	144, 417-420	—, Member of Auditing Committee.....	49
— of Utah.....	144	VEATCH, A. C., Geological work in Arkansas of.....	167
— Tertiary.....	417	— cited on the Livingston unconformity.....	348
ULRICH, E. O., cited on diastrophic activity.....	335	— pre-Lance unconformity.....	328
— fossil sponges.....	272	VERBEEK, R. D. M., cited on Melaphyres.....	610
— oolites.....	764	VERMEJO formation, Flora of the.....	331-333
— Ordovician-Silurian boundary.....	331	VERMONT, Pre-Cambrian unconformity in.....	39
—, Discussion of corrosion conglomerate by.....	39	VERTEBRATE faunas, Interpretation of.....	390-393
— Silurian system of Ontario by.....	41	— fauna of the Orindan and Siestan formations; J. C. Merriam.....	156
UNITED STATES, Chart of storm belt of.....	570	—, Triassic limestones at Cow Creek, Shasta County, California; H. C. Bryant.....	155
— tracks in the.....	498	VERTEBRATES, Range in typical American formation of land.....	387
		VOLCANIC hypothesis of climatic changes.....	483
		VON HUMBOLDT, A., Geological work in Texas of.....	164

	Page
VON HUMBOLDT, A., Reference to Coastal Plain work by.....	159
VON WOLFF, F., cited on pillow structure	636
WAAGEN, "Mutations" of.....	142
WABANA iron ores of Newfoundland...	74
WAILLES, B. L. C., Geological work in Mississippi of.....	170
WALCOTT, C. D.; Cambrian of western North America.....	130
— cited on Cambrian brachiopoda.....	421-422
— — Paleozoic intraformational conglomerate	265-276
—, Delivery of presidential address, entitled "The Cambrian of western North America," by.....	65
—, Discussion of pre-Cambrian unconformity in Vermont by.....	40
WALES, Pillow lavas of.....	601
WALKER, F. A., Reference to support given to research by.....	176
WALKER, G. T., cited on climatic changes in India.....	481
WALKER, T. L.; Temiskamite, A new nickel arsenide from Ontario.....	76
WALLACE, R. C., cited on Ordovician limestone in Manitoba.....	270
WALTHER, J., cited on origin of oolites.....	751
WAMSUTTA Red beds of Narragansett series	447
— volcanoes	462
WARD, R., cited on measurement of elephants	407
WARING, C. H.; Geological relations between the Cretaceous and Tertiary of southern California.....	152
— cited on basin terraces in Oregon.....	561
WARREN, C. H., Analysis of Quincy granite by.....	466
— and S. POWERS; Geology of the Diamond Hill-Cumberland district in Rhode Island-Massachusetts....	75, 435
— cited on pre-Cambrian gabbro.....	450
— — minerals	451
— — Quincy granite.....	464
— riebeckite granite.....	470
WASATCH equivalent to Sparnacian and Ypresian	396
— fauna compared with other faunas..	387
WASHINGTON, Coal-bearing Eocene of..	121
—, Lower Miocene of.....	153
WATER deposits, Mechanical analyses of	693-712
— sediments, Differences between wind and	740
WATSON, T. L., Memorial of W. M. Fontaine by.....	6
WEAVER, C. E., cited on Cretaceous-Eocene boundary.....	343
—, Lower Miocene of Washington.....	153
WEBER, A. H., Discussion of California rainfall by.....	121
— — climatic provinces by.....	124
— — Haywards Rift by.....	123
— — nomenclature by.....	125
WEED, W. H., cited on ore deposits.....	770
— — stratigraphic relations of Livingston formation.....	346
— — unconformity at base of the Livingston	346
WEIDMAN, S., cited on pillow lavas....	616
WELLER, S., and M. G. MEHL; Western extension of some Paleozoic faunas in southeastern Missouri.....	135
WETHERED, E. B., cited on origin of oolites	749
WESTERN extension of some Paleozoic faunas in southeastern Missouri; S. Weller and M. G. Mehl.....	135

	Page
WESTERN fuel section of U. S. Geological Survey, Reference to.....	349
WEST VIRGINIA, Deepest boring in.....	48
WHEELER, Mrs. H. I., Acknowledgments to	123
WHIPPLE, C. L., cited on pillow lavas..	623
WHIPPLE, LIEUT., Reference to surveys in Texas by.....	165
WHITE, C. A., cited on Colorado invertebrate fauna.....	327
— — geologic time scale.....	336
WHITE, DAVID, Discussion of corrosion conglomerate by.....	37
— — symposium papers by.....	130
—, Introduction of E. C. Jeffrey by.....	58
WHITE, I. C., Deepest boring in West Virginia	48
—, Memorial of T. M. Jackson by.....	13
—, Permian glaciation in Brazil discussed by.....	31
WHITEHEAD, W. L., cited on riebeckite granite	470
WHITLEY, N., cited on pillow lava.....	604
WIELAND, G. R., cited on oolites....	760-761
WILCOX formation.....	330
—, Flora of the	332, 333
WILCOX, G. A., Discussion of Haywards Rift by.....	123
WILLIAMS, E. H., cited on Clarendon gravels	217, 218
— — distribution of copper in glacial deposits	213
WILLIAMS, G. H., cited on origin of pillow lavas.....	637
— — spheroidal greenstone schists..	613
WILLIAMS, J. L., Geological work in Florida of.....	174
WILLIAMS, M. Y., cited on Cabots Head section, Ontario.....	319
— — Manitowaning section, Ontario.....	320
— — Clinton formation.....	279
—, Photographs by [plate 14].....	287
—, Sections illustrating the lower part of the Silurian system of southwestern Ontario.....	40
WILLIS, JOHN, Fossil locality at ranch-house of.....	357
WILLISTON, S. W., cited on Mæstrichtien stage	321
WILLISTON, —, Reference to model described by.....	143
WILKES Expedition, Reference to fossils collected by.....	162
WILLMOTT, A. B., cited on elliptical greenstone schists.....	612
— — pillow lavas.....	616
WINCHELL, N. H., cited on ellipsoidal greenstone	613-614
— — origin of pillow lavas.....	637
— — pillow lavas.....	619
—, Delaware terraces.....	86
—, Discussion of Glacier Bay topography by.....	89
— — intraformational corrugation..	37
— — Ontario glaciation by.....	72
—, Reference to speech at dinner by.....	80
—, Review of the formation of geological societies in the United States	27
WINCHESTER, D. E., cited on Cannonball formation.....	339
— — geology of Indian reservations.....	350
WIND deposits, Mechanical analyses of	713-726
— sediments, Differences between water and	740
WINDLE, —, cited on anatomy of horse and tapir.....	406
WOOD, E., Use of crinoid arms in studies of phylogeny.....	135
WOODWARD, HENRY, elected honorary member of Paleontological Society.....	134

	Page		Page
WOODWORTH, J. B., cited on Blackstone series	444-445	WYOMING, Conglomerate of	346
— — — Diamond Hill quartz deposits ..	471	—, Continuity of marine sedimentation in	345
— — — glaciation in Brazil	31	—, Cretaceous-Eocene correlation in ..	355
— — — Wamsutta volcanoes	462	—, Lance formation of	348
—, Work in the Diamond Hill-Cumberland district by	438-441	—, Mammal-bearing beds of	325
WOLF, ———, Comparison of sun-spots and hurricanes by	494	—, Mesaverde formation in	345
WOLFER'S sun-spot numbers, Reference to	485	YALE Museum, Accessions to exhibition series at	143
WRIGHT, F. E., and G. A. RANKIN; Physical-chemical system, lime-alumina-silica and its geological significance	92	YEATES, W. S., Geological work in Georgia of	174
—; Change in the crystallographical and optical properties of quartz with rise in temperature	44	YOUNGS, L. J., Analysis of concretions by	79
WRIGHT, G. F.; Age of the Don River glacial deposits, Toronto, Ontario ..	71, 205	YPRESIAN and Sparnacian equivalent to Wasatch	396
—; Evidence of a glacial dam in the Allegheny River between Warren, Pennsylvania, and Tionesta	84, 215	YUCATAN, Climatic changes in	539
WYOMING, Coal-bearing formations in ..	345	YUKON-ALASKA boundary line, Geological section along the	179
		ZACCAGNA, D., cited on spheroidal diabase	600
		ZIEGLER, V., cited on oolites ..	761-762, 764

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